



DCN: 87-245-019-04

HEAVY-DUTY DIESEL VEHICLE  
INSPECTION AND MAINTENANCE STUDY

FINAL REPORT  
VOLUME I

SUMMARY REPORT

Submitted to:

California Air Resources Board  
1800 15th Street  
P.O. Box 2815  
Sacramento, CA 95812

ARB Contract No. A4-151-32

Submitted by:

Christopher S. Weaver, P.E.  
Project Director

Robert F. Klausmeier  
Program Manager

Radian Corporation  
10395 Old Placerville Road  
Sacramento, CA 95827

May 16, 1988

The statements and conclusions in this report are those of the Contractor and are not necessarily those of the State Air Resources Board. The mention of commercial products, their source or their use in connection with material reported herein is not to be considered as an actual or implied endorsement of such products.

## LIST OF TABLES

<u>Table</u>	<u>Title</u>	<u>Page</u>
2-1	Common Types of Emissions-Related Defects in Heavy-Duty Diesel Trucks.....	2-2
2-2	Survey of Diesel Mechanics and Maintenance Managers: Questionnaire Results.....	2-9
2-3	Comparison of Radian Fleet-Average Emission Factor Estimates with EMFAC7C.....	2-15
2-4	Contributions of Each Heavy-Duty Vehicle Class to Total Statewide Emissions.....	2-16
2-5	Contributions of Total Excess Emissions by Each Heavy-Duty Vehicle Class.....	2-18
3-1	Proposed Periodic I/M Test Procedures.....	3-4
3-2	Effectiveness of Smoke Opacity Tests in Identifying High Emitters.....	3-16
3-3	Pass/Fail Analysis for Two Sets of I/M Failure Criteria: New York Bus Database.....	3-24
4-1	I/M Scenarios Considered.....	4-3
4-2	Estimated Costs and Cost-Effectiveness of I/M Programs, 1990.....	4-14
4-3	Estimated Costs and Cost-Effectiveness of I/M Programs, 1995.....	4-15
4-4	Estimated Costs and Cost-Effectiveness of I/M Programs, 2000.....	4-16

## LIST OF FIGURES

<u>Figure</u>	<u>Title</u>	<u>Page</u>
ES-1a	Projected NO <sub>x</sub> Emissions from Heavy-Duty Diesels: 1985-2000.....	viii
ES-1b	Projected HC Emissions from Heavy-Duty Diesels: 1985-2000.....	ix
ES-1c	Projected PM Emissions from Heavy-Duty Diesels: 1985-2000.....	x
ES-2	Breakdown of PM Emissions by vehicle class: 1990.....	xii
ES-3	Acceleration Peak Smoke Opacities from the Screening Tests.....	xiv
ES-4	Visual Opacity Estimates vs. Opacimeter: Acceleration Peak.....	xv
ES-5	Acceleration Smoke Opacity vs. PM: New York Bus 2 Cycle...	xvii
ES-6	Emissions Reductions Projected for Alternative I&M Programs : 1990.....	xxi
ES-7	Emissions Reductions Projected for Alternative I&M Programs: 2000.....	xxi
ES-8	Percent Reduction in Excess Emissions for Alternative I&M Programs: 1990.....	xxii
ES-9	Percent Reduction in Excess Emissions for Alternative I&M Programs: 2000.....	xxii
ES-10	Estimated Costs of Alternative I&M Programs: 1990.....	xxiii
ES-11	Estimated Costs of Alternative I&M Programs: 2000.....	xxiv
ES-12	Estimated Cost-Effectiveness of Alternative I&M Programs for Particulate Emissions Control.....	xxvi
2-1	Distribution of Truck Smoke Opacity in Road-Load Operation.....	2-4
2-2	Distribution of Truck Smoke Opacity in Full-Power, Steady-State Operation.....	2-5
2-3	Distribution of Truck Smoke Opacity Under Transient Acceleration.....	2-6

2-4	Projected Statewide NO <sub>x</sub> Emissions from Heavy-Duty Diesel Vehicles.....	2-11
2-5	Projected Statewide HC Emissions from Heavy-Duty Diesel Vehicles.....	2-12
2-6	Projected Statewide PM Emissions from Heavy-Duty Diesel Vehicles.....	2-13
3-1	Bar Chart of Peak Acceleration Smoke Opacities from the Field Screening.....	3-6
3-2	Visual vs. Measured Smoke Opacity (Acceleration Peak).....	3-10
3-3	Measured vs. Visual Smoke Opacity (Snap Idle Peak Reading)	3-11
3-4	Particulate Emissions vs. Lug-Down Opacity.....	3-13
3-5	Particulate Emissions vs. Acceleration Peak Smoke Opacity.	3-14
3-6	NO <sub>x</sub> Emissions vs. Mode 4 Concentrations.....	3-18
3-7	Predicted vs. Actual HC (Based on Modes 6 & 14).....	3-19
3-8	Acceleration Smoke Opacity vs. Particulate Emissions (New York Bus 2 Cycle).....	3-21
3-9	Actual Particulate Emissions vs. Emissions Predicted from Acceleration and Cruise Mode Opacities: New York Bus Composite.....	3-22
3-10	Actual Particulate Emissions vs. Emissions Predicted from Acceleration and Cruise Mode Opacities: New York Truck Cycle.....	3-23
4-1	Comparison of I/M Scenarios: Total Emissions - 1990.....	4-7
4-2	Comparison of I/M Scenarios: Total Emissions - 1995.....	4-8
4-3	Comparison of I/M Scenarios: Total Emissions - 2000.....	4-9
4-4	Comparison of I/M Scenarios: Reduction in Emissions Due to I/M.....	4-10
4-5	Comparison of I/M Scenarios: Percent Reduction in Excess Emissions Due to I/M.....	4-11
4-6	Comparison of I/M Scenarios: Reduction of Offensive Smoke Due to I/M.....	4-13
4-7	Comparison of I/M Scenarios: Program Costs and Cost-Effectiveness.....	4-18

HEAVY DUTY DIESEL VEHICLE  
INSPECTION AND MAINTENANCE STUDY

EXECUTIVE SUMMARY

Heavy-duty diesel vehicles are responsible for significant emissions of oxides of nitrogen ( $\text{NO}_x$ ), unburned hydrocarbons (HC), and particulate matter (PM) in urban areas in California. As with other types of vehicles, poor maintenance and/or tampering with emissions controls can greatly increase these emissions. Up to now, however, diesel vehicles in most states have been exempt from any type of inspection and maintenance (I/M), such as California's Smog Check Program. This is due to the lack of a well-documented emissions test procedure for diesels, and to uncertainty as to the cost-effectiveness of such a program.

In order to address these issues, the California Air Resources Board (ARB) issued contract no. A4-151-32 to Radian Corporation, for a study which would:

- Quantify the extent of excess emissions from heavy-duty diesel vehicles due to malmaintenance and/or tampering;
- Develop and validate suitable I/M procedures for heavy-duty diesel trucks and buses; and
- Estimate the costs and emissions benefits of implementing a heavy-duty diesel I/M program.

The study results indicate: that excess emissions from heavy-duty diesels are significant; that suitable procedures for detecting high-emitting vehicles exist; and that a suitability designed I/M program could be very cost-effective compared to other diesel emissions control measures that have been adopted.

QUANTIFYING THE PROBLEM

To quantify the problem of excess emissions, a computer model of total and excess emissions from heavy-duty diesel vehicles was developed. Excess emissions are calculated from estimates of the emissions levels of properly functioning vehicles and estimates of the effects and frequency of occurrence of 18 types of emissions-related defects. Defect frequency estimates were based on a visual survey of truck smoke opacity on California freeways and a questionnaire survey of diesel fleet maintenance managers and mechanics. The impact of each type of defect on emissions was estimated using data from several sources. Key data sources were an EPA/Engine Manufacturers' Association cooperative test program; laboratory studies by EPA and Southwest Research Institute; and a database compiled by the New York City Department of Environmental Protection covering more than 400 emissions tests on trucks and buses. This last was computerized and analyzed for the first time as part of this study.

The computer model of diesel emissions and tampering/maintenance effects constructed for this study deals with four general classes of heavy-duty diesel vehicles: heavy-heavy, medium-heavy, light-heavy, and transit bus. The model further differentiates between out-of-state and California-registered vehicles, and between California-registered vehicles with California and Federal engines. The model can also be used to estimate the impact of a given I/M program on emissions.

The emissions model results for the case with no I/M program are plotted in Figure 1. This figure displays the annual average statewide tons per day of  $\text{NO}_x$ , HC, and PM emitted by heavy-duty diesel vehicles, broken down into baseline and excess emissions. The baseline emissions level is the amount that would be emitted even if all the engines in use were in good mechanical condition and with their emission controls performing properly. Excess emissions are defined as the increase over and above the baseline due to tampering, maintenance, and excessive engine wear. As Figure 1 shows, excess emissions account for a rather small fraction of heavy-duty diesel  $\text{NO}_x$  emissions, but a large and increasing fraction of HC and PM emissions.

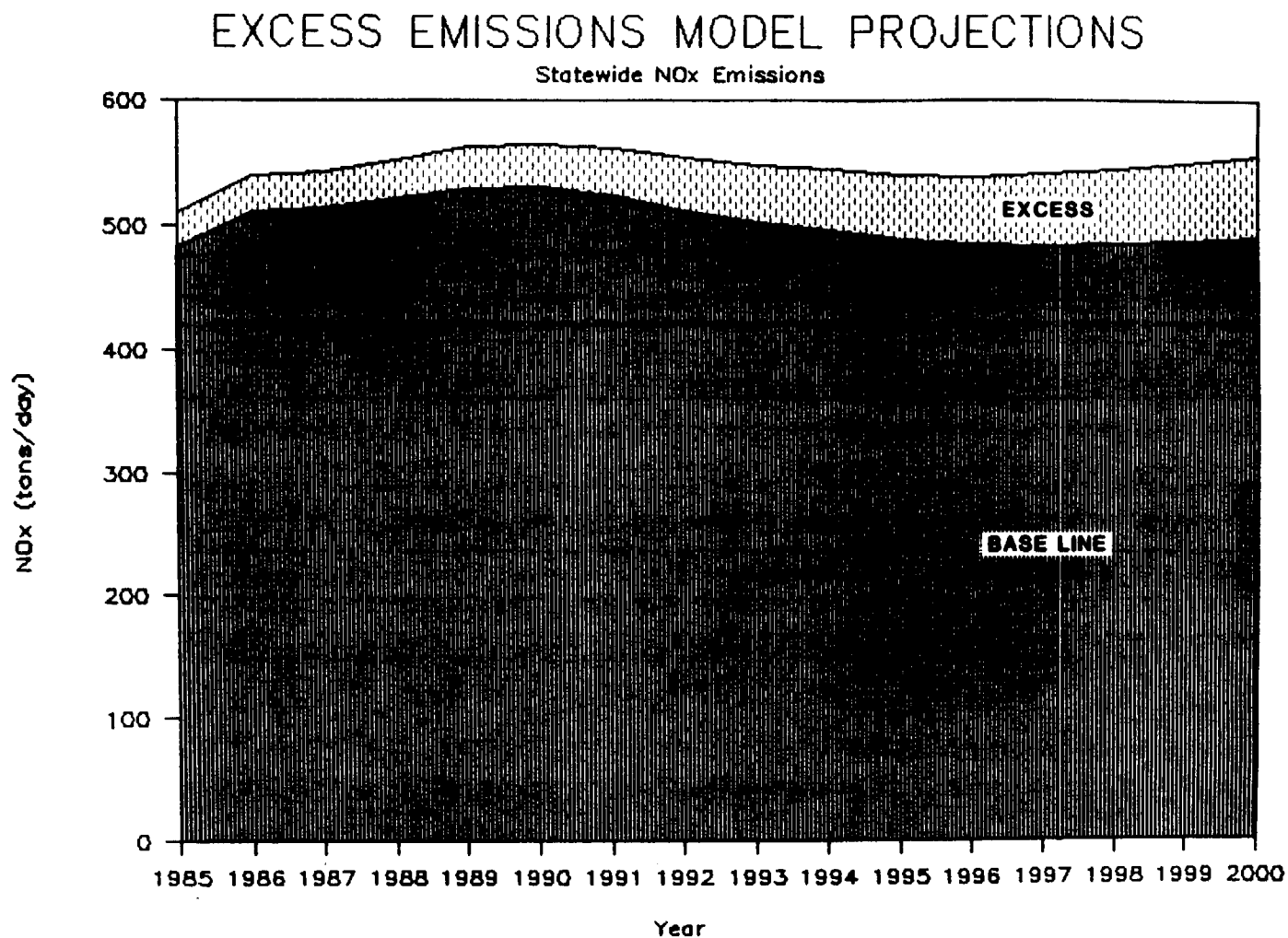


Figure ES-1a: Projected NOx Emissions from Heavy-Duty Diesels: 1985-2000.

## EXCESS EMISSIONS MODEL PROJECTIONS

Statewide HC Emissions

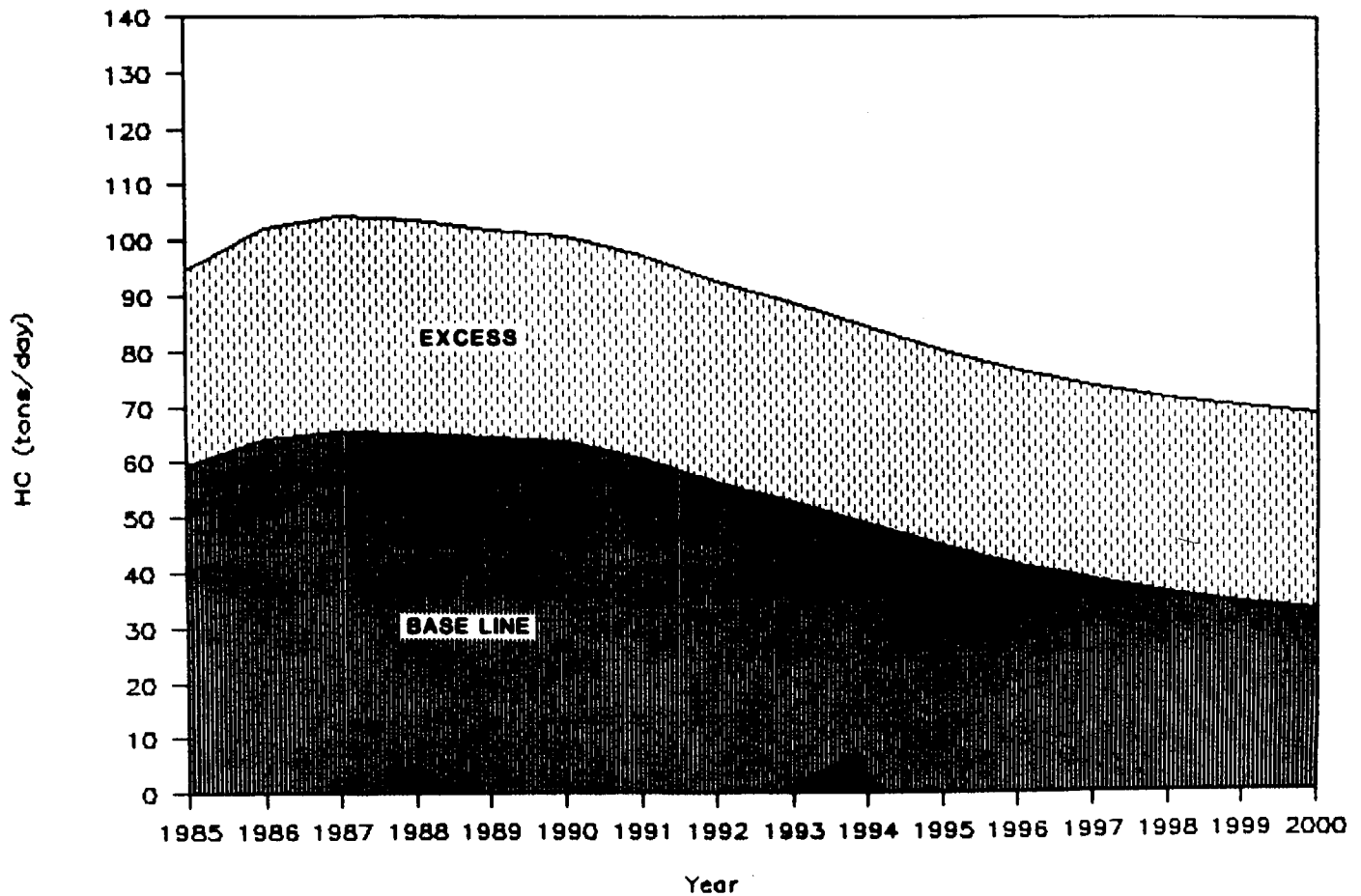


Figure ES-1b: Projected HC Emissions from Heavy-Duty Diesels: 1985-2000.

## EXCESS EMISSIONS MODEL PROJECTIONS

Statewide PM Emissions

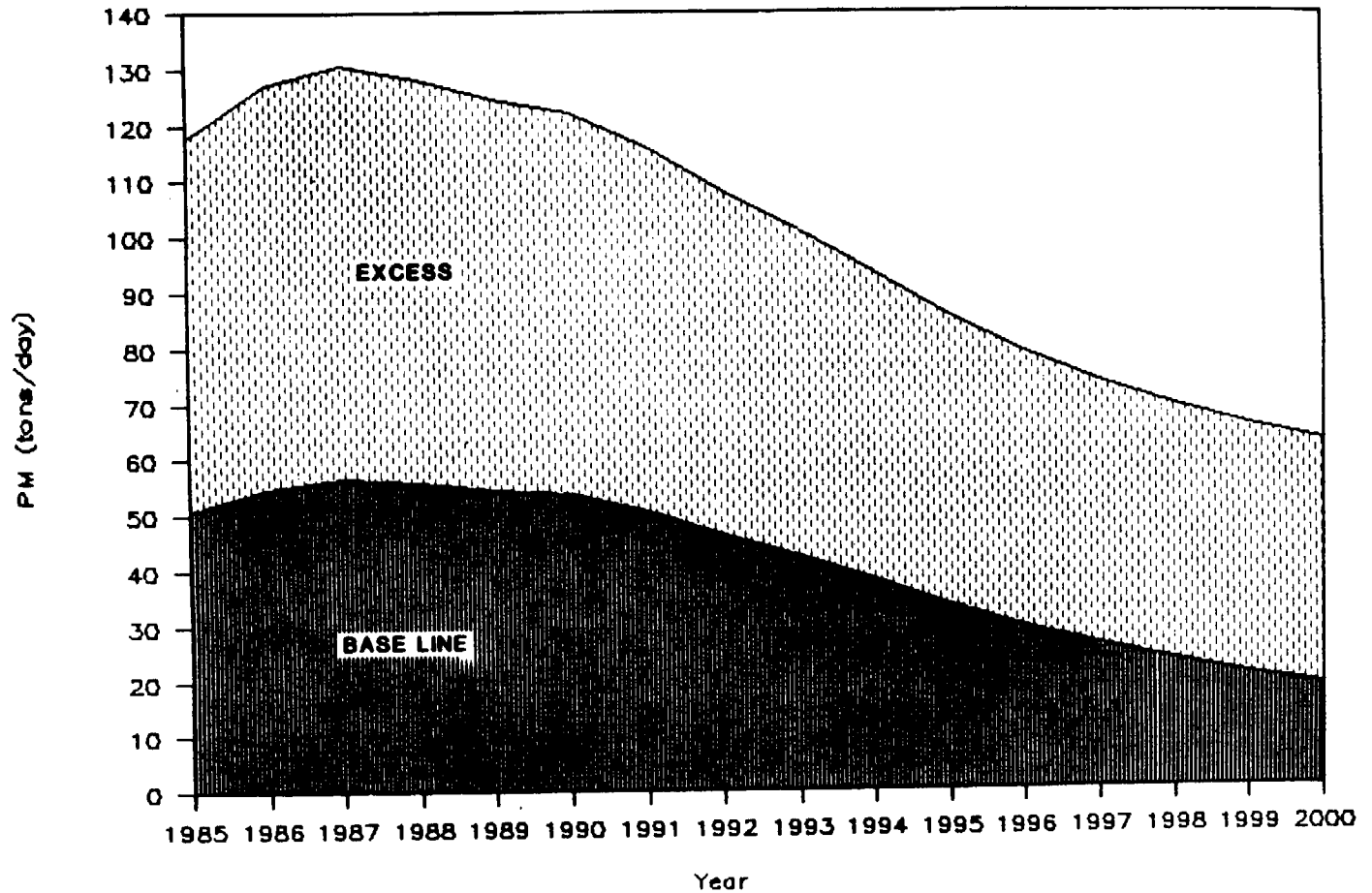


Figure ES-1c: Projected PM Emissions from Heavy-Duty Diesels: 1985-2000.

Figure 2 shows the projected breakdown of total PM emissions between the different classes of heavy-duty vehicles for the year 1990 (breakdowns for HC and NO<sub>x</sub>, and for other years, show a similar pattern). As the figure indicates, nearly all of these emissions are due to heavy-heavy and medium-heavy trucks, with heavy-heavy vehicles alone accounting for about two thirds. Light-heavy duty vehicles and transit buses are responsible for a relatively minor share. Out-of-state vehicles are fairly significant contributors to the overall emissions levels, but California-registered vehicles with Federal engines are even more significant. Together, these two groups account for about one-half of the total heavy-duty diesel emissions in California.

Because of the lack of applicable statistical data to base them on, these projections include considerable uncertainty. The range of uncertainty in the excess emissions estimates is estimated at -30 percent to +70 percent of the value shown, while the uncertainty in the total emissions is estimated at approximately -20 to +50 percent.

#### DEVELOPMENT AND VALIDATION OF I/M TEST PROCEDURES

Two types of inspection test procedures for heavy-duty diesel vehicles were developed and validated: a Periodic Inspection and Maintenance Test (PIMT) procedure and a Roadside Smoke Opacity Check (ROC). The purpose of each of these procedures is to identify heavy-duty diesel vehicles which are producing excessive pollutant emissions. The ROC is intended to be used for random enforcement testing. For this reason, it was required that it be performable within the physical confines of a California Highway Patrol (CHP) weigh station. The PIMT, as its name implies, is intended to be used in a periodic (e.g. annual or biennial) inspection program, analogous to California's existing Smog Check Program.

A number of candidate ROC and PIMT procedures were developed and subjected to validation testing. The ROC was applied to 52 heavy-duty diesel trucks belonging to various government agencies and private fleets. The results of the ROC screening were used to select eleven trucks for PIMT

PM EMISSIONS BREAKDOWN BY CLASS: 1990

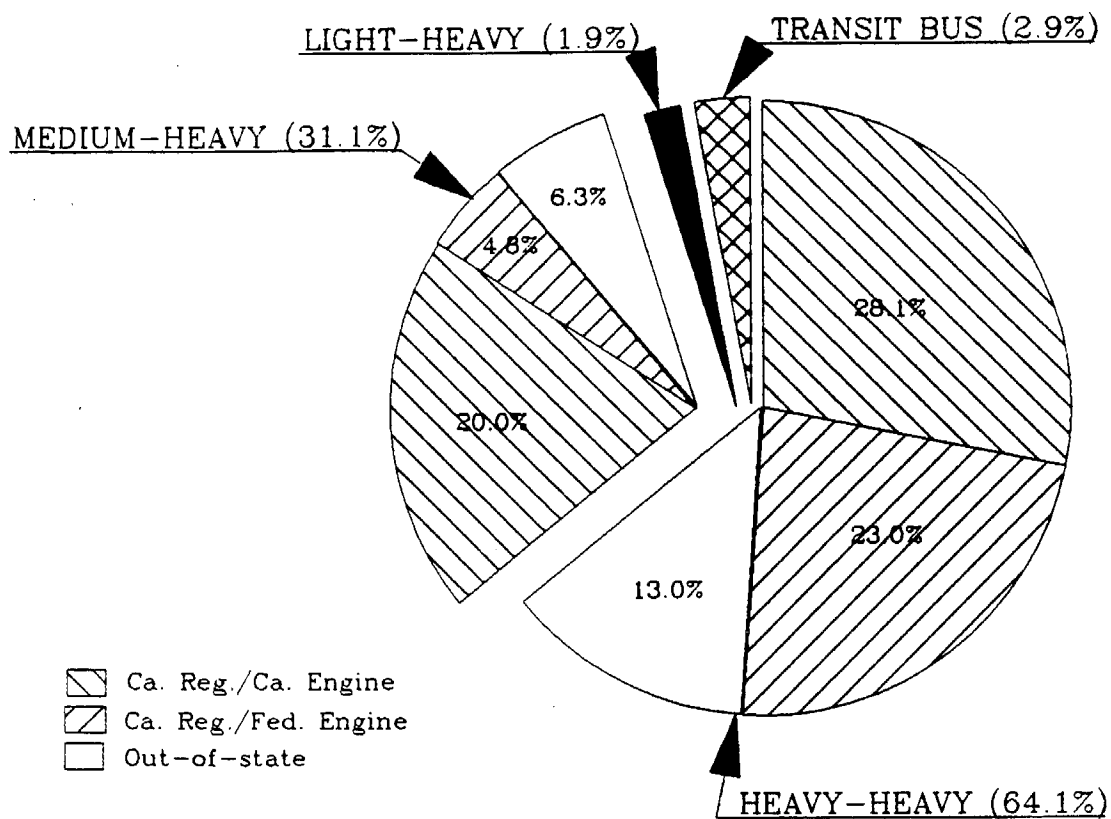


Figure ES-2: Breakdown of PM Emissions by Vehicle Class: 1990.

testing at ARB's Haagen-Smit Laboratory facility. Mass emissions measurements were also taken on these trucks, using a chassis-dynamometer version of the old 13-mode emissions test. Six of these vehicles were then repaired in an attempt to reduce their emissions, and then retested. In addition, smoke test data from the NYCDEP database were analyzed to determine their correlation with mass PM and HC emissions.

The most effective ROC test procedure was found to be measuring peak smoke opacity during a full-power vehicle acceleration from a stop. Figure 3 displays the validation test results using this procedure. The trucks selected for dynamometer testing are indicated by the arrows underneath the figure. Another test procedure--measuring smoke opacity as the engine accelerates from idle to the torque-converter stall speed--was found to give similar results. This procedure is safer and requires less space than the vehicle acceleration, but applies only to vehicles with automatic transmissions. Two other test procedures gave poor results. These were: quick acceleration to the engine's governor speed; and lugging-down the engine against the brakes.

Smoke opacity measurements in the ROC testing were made with an end-of-stack opacity meter mounted on the truck. Opacity was also estimated visually by an ARB employee. Figure 4 is a cross plot comparing these two measurements for the acceleration peak data. Cross-hairs indicating our proposed failure criterion for that mode are also shown on the plot. These data indicate a fair degree of correspondence between the visual opacity estimates and the opacimeter data in the moderate-to-high opacity range. This suggests that a visual screening approach could be feasible with the ROC, greatly simplifying its implementation in the field. An officer could distinguish passing from failing levels by eye in most cases. Marginal or protested cases could then be confirmed using an opacimeter.

Statistical analysis of the PIMT data showed poor correlation between acceleration smoke opacity and 13-mode particulate emissions. This was due to the presence of two vehicles with high transient acceleration smoke, but low emissions on the 13-mode test (which is conducted under steady-state conditions). This test is incapable of measuring emissions which occur

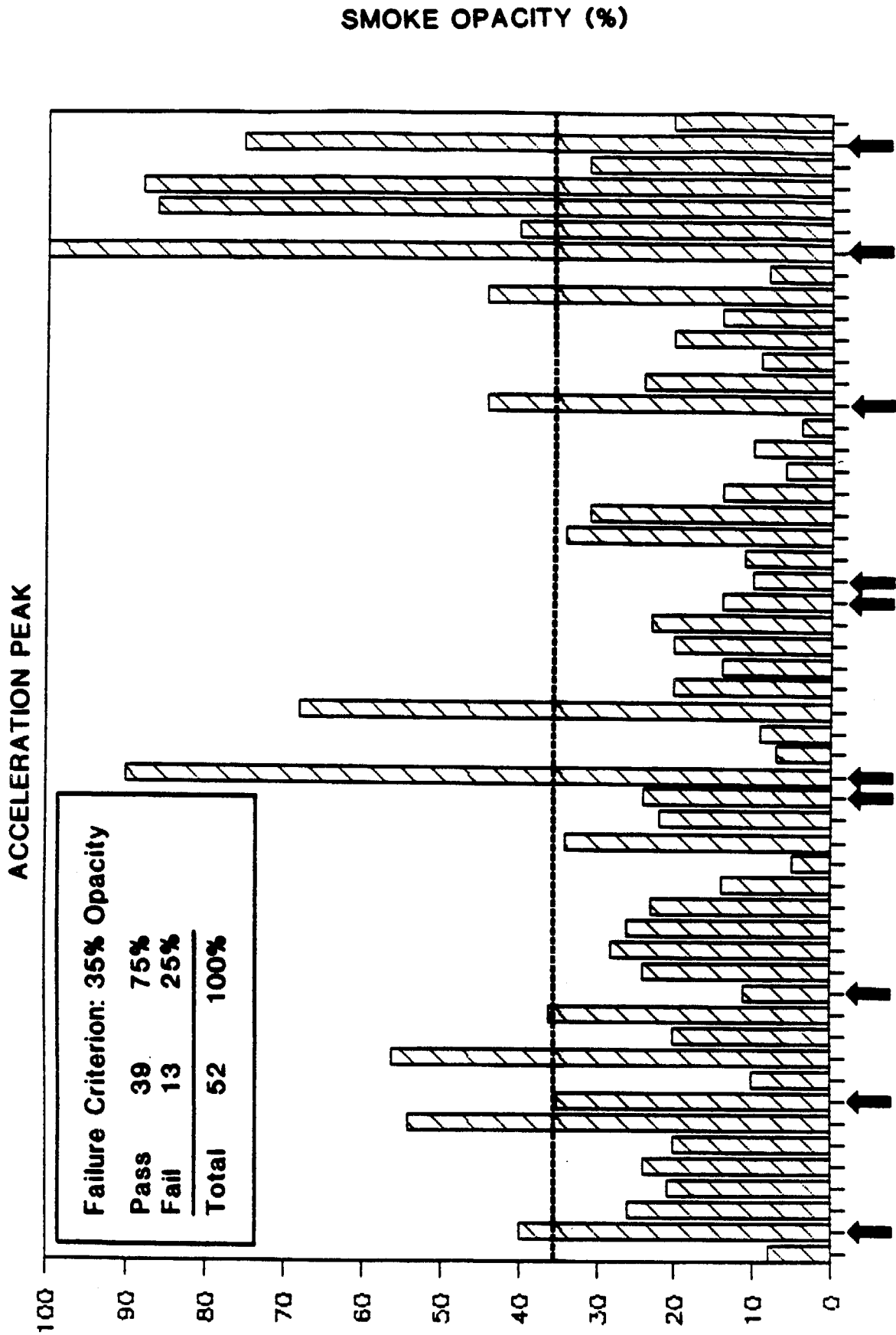


Figure ES-3: Acceleration Peak Smoke Opacities from the Screening Tests.

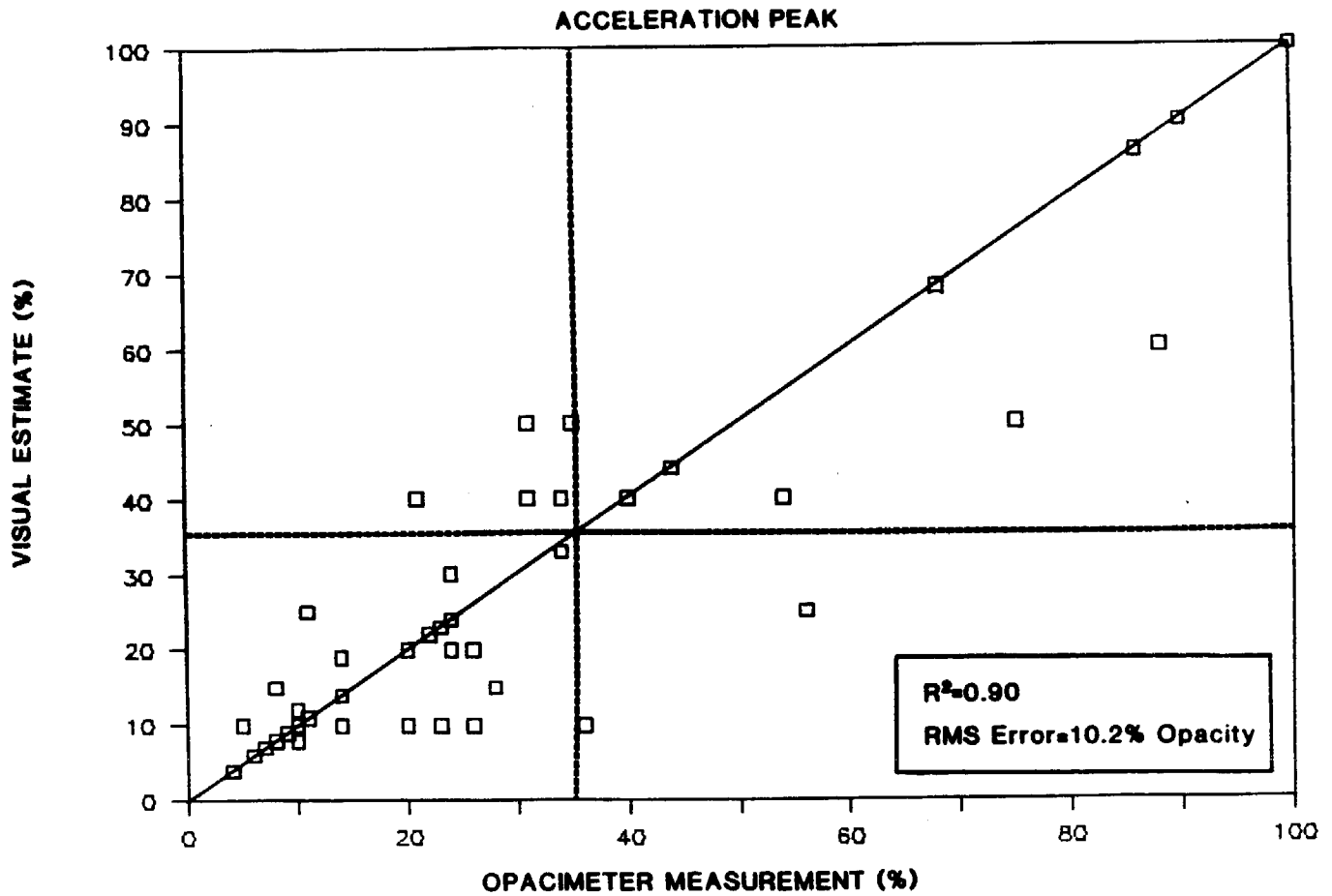


Figure ES-4: Visual Opacity Estimates vs. Opacimeter: Acceleration Peak.

only under transient conditions. A similar statistical analysis was conducted on the NYCDEP database, which included both acceleration smoke measurements and mass emissions measured under transient conditions. This analysis showed good correlation between acceleration smoke and total PM. These data are shown in Figure 5.

We examined the effectiveness of the acceleration smoke opacity test in detecting high-emitting vehicles. For the PIMT validation tests, a failure criterion of 35 percent opacity resulted in seven failures, accounting for 71 percent of the excess PM emissions. Two of these failures were "errors of commission"--vehicles with high acceleration smoke opacity but low 13-mode emissions (these were the same vehicles that caused the poor correlation discussed above). As discussed above, however, these vehicles would likely have shown higher emissions on a transient emissions test.

A similar analysis was conducted on the bus portion of the NYCDEP database. Of this fleet, 69.3 percent were low emitters, and all of these passed the I/M test (there were no errors of commission). The remaining 30.7 percent of the buses were classed as high emitters. Of these, more than two-thirds (20.8 percent of the total) also passed the I/M test, causing them to be classed as errors of omission). Only 9.9 percent of the buses failed the I/M test. However, this small group accounted for more than 68 percent of the total excess particulate emissions and 80 percent of excess hydrocarbon emissions for the entire fleet. Mean emissions from the failing group were 26.7 g/mi of particulate, which is nearly nine times the mean for the low-emitting group, and three times the mean for the false negative group. Thus, while these tests did not detect all high emitters, they did detect the highest emitters, which account for most of the excess emissions.

#### COSTS AND EMISSION BENEFITS OF HEAVY-DUTY DIESEL I/M

After analyzing the results of the preceding phases, a number of alternative I/M scenarios were defined. These were input into the heavy-duty

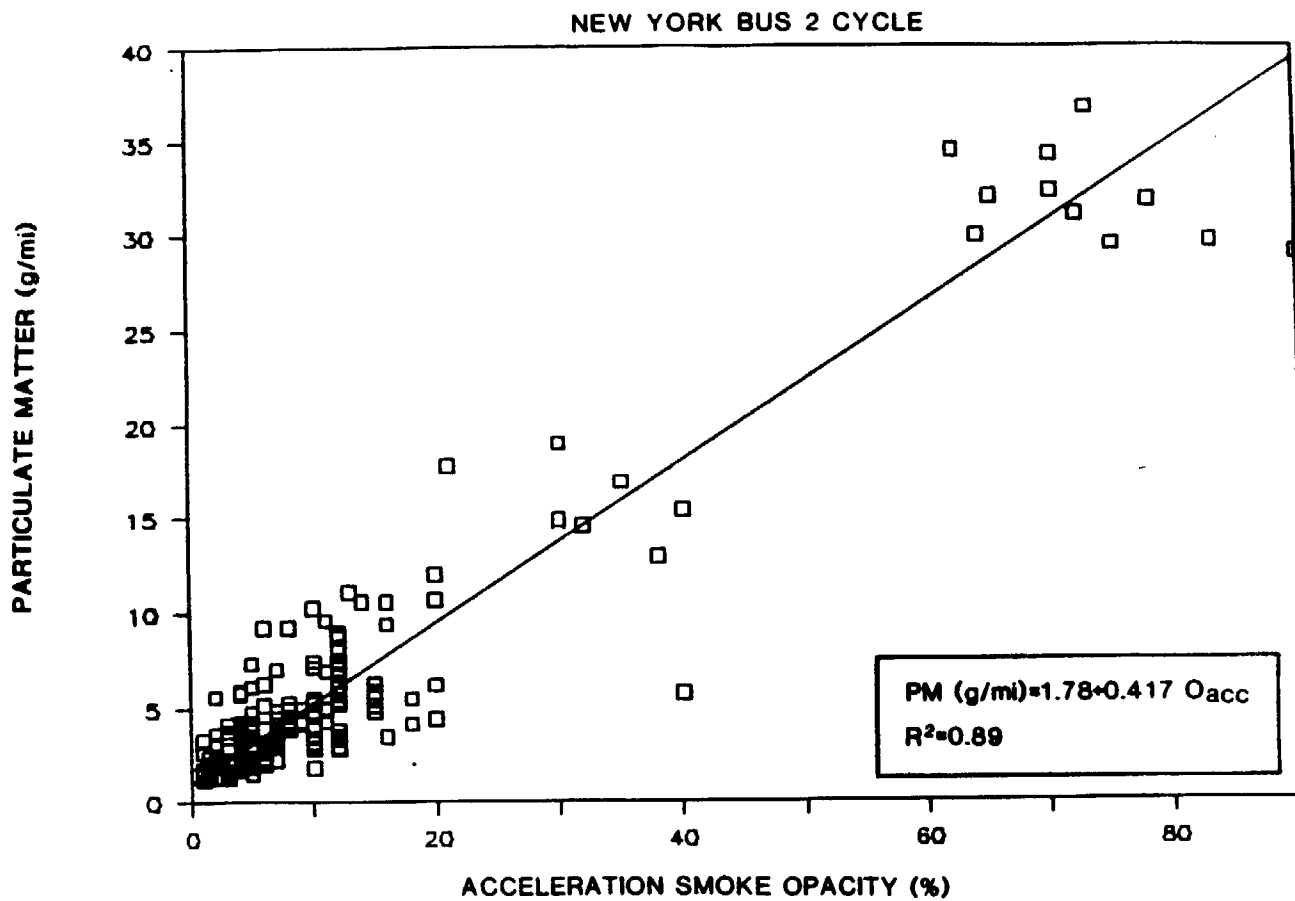


Figure ES-5: Acceleration Smoke Opacity vs. PM: New York Bus 2 Cycle.

diesel emissions model developed in Task One. This model was used to calculate the change in emissions as a result of each I/M scenario, as well as repair costs and related data.

#### Alternative I/M Program Designs

Because of the differences in technology, ownership, and operating patterns, existing I/M programs for light-duty vehicles may not be a good model for heavy-duty diesel I/M. Other existing enforcement programs aimed at heavy-duty trucks (such as Highway Patrol weigh stations and safety inspection programs) should be considered as well. To reduce emissions, while minimizing the burden on vehicle owners, the primary goals of a heavy-duty diesel I/M program should be the following:

- Deter tampering with emission controls;
- Detect tampering which is not deterred, and require that it be corrected;
- Identify gross-emitting vehicles, and require that they be repaired; and
- Encourage proper maintenance and awareness of the importance of emission controls in the bulk of the heavy-duty diesel fleet.

The I/M program scenarios investigated in this study were chosen with these goals in mind. They consist of a number of variations on two basic approaches: a dynamometer-based periodic I/M program, and a program of in-use smoke opacity enforcement and random anti-tampering inspections.

Case 1, the basic periodic I/M scenario, consists of periodic, annual inspections enforced through the registration process. It assumes a decentralized, garage-based inspection program, using chassis dynamometer test procedures for smoke opacity and gaseous pollutant concentration in specific

operating modes. In addition, an anti-tampering inspection and functional check of emission controls such as EGR valves, trap-oxidizers, timing advance units, etc. is included. The basic scenario includes a \$1,000 cost limit for repairs, with no cost limit for correcting tampering. Cost waivers require approval by a referee station.

Cases 1a through 1f consist of variations on this basic scenario. In Case 1a, inspection is performed in central, state-operated inspection stations, rather than in truck garages. In Case 1b, the repair cost limit is reduced to \$500. In Case 1c, the repair cost limit is eliminated--i.e. "fix it or park it". In Case 1d, the gaseous pollutant concentration measurements are eliminated. Case 1e is a biennial inspection program. Case 1f, the final variation, reflects the legal constraints of the current Smog Check legislation in California. These include: biennial inspection, \$100 cost limit, and a limit on the charge for a Smog Certificate of \$6.

Case 2 describes a very different I/M program, based on in-use smoke opacity enforcement and anti-tampering inspections. This would include stationing ARB Smoke Inspectors at CHP truck scales and inspection stations to maintain continuous visual screening for excessive smoke, and with the authority to pull a truck over for a smoke test and/or anti-tampering inspection. Trucks cited for excessive smoke would be required to be repaired and test below the standards within two weeks, unless they receive a cost waiver. The cost limit for repairs in the basic scenario is \$1,000 (a variant, Case 2a, eliminates the cost limit). Smoke tests after repairs may be performed by authorized garages. Trucks cited for excessive smoke more than once in 6 months are subject to a \$250 fine (except where the first citation resulted in a waiver). Tampering with emission controls, or knowingly operating a truck with tampered controls, is subject to a \$1,000 fine for the first offense, and \$2,500 fine for each subsequent occurrence. Tampering must be corrected within two weeks, with no cost limit.

In addition, ARB Inspectors would accompany CHP depot truck inspection teams to conduct anti-tampering inspections at the same time the CHP

conducts safety inspections. At the same time, the existing truck smoke law would be tightened, and local police forces trained in enforcing it. Dedicated roving smoke patrol officers would be assigned in critical air pollution areas such as the South Coast Air Basin.

### Results

Emissions--Figures 6 and 7 show the projected reduction in  $\text{NO}_x$ , HC, and PM emissions in California due to each alternative I/M program. Figure 6 shows the results projected for 1990, and Figure 7 those for 2000. Figures 8 and 9 show the percentage reduction in excess emissions due to each program.

As these figures indicate, all of the annual inspection programs are reasonably effective in reducing excess  $\text{NO}_x$ , but they are less effective in reducing HC and PM emissions. The centralized program in Case 1a is marginally more effective in this regard, reflecting the greater probability of deterring or detecting tampering with the central inspection. All of these programs are hampered, however, by their relatively infrequent and predictable inspections, which limit the deterrence of "reversible" tampering, and which do relatively little to reduce the overall incidence of non-tampered high-emitting vehicles.

The in-use inspection programs, on the other hand, are highly effective in reducing particulate and HC emissions--resulting in more than a 50 percent reduction in excess PM. These programs are less effective in reducing  $\text{NO}_x$ , however, due to the inability to perform gaseous emissions measurements in the field.

Costs and Cost-Effectiveness--Overall costs for each alternative program are shown in Figures 10 and 11. Figure 10 shows the annual costs for 1990, while Figure 11 shows the costs for 2000. The breakdown of costs into administration and enforcement, inspection, repairs, indirect costs, and fines is also shown. Indirect costs include lost driver and vehicle time due to inspections, and the costs (or benefits) of changes in fuel economy.

1990

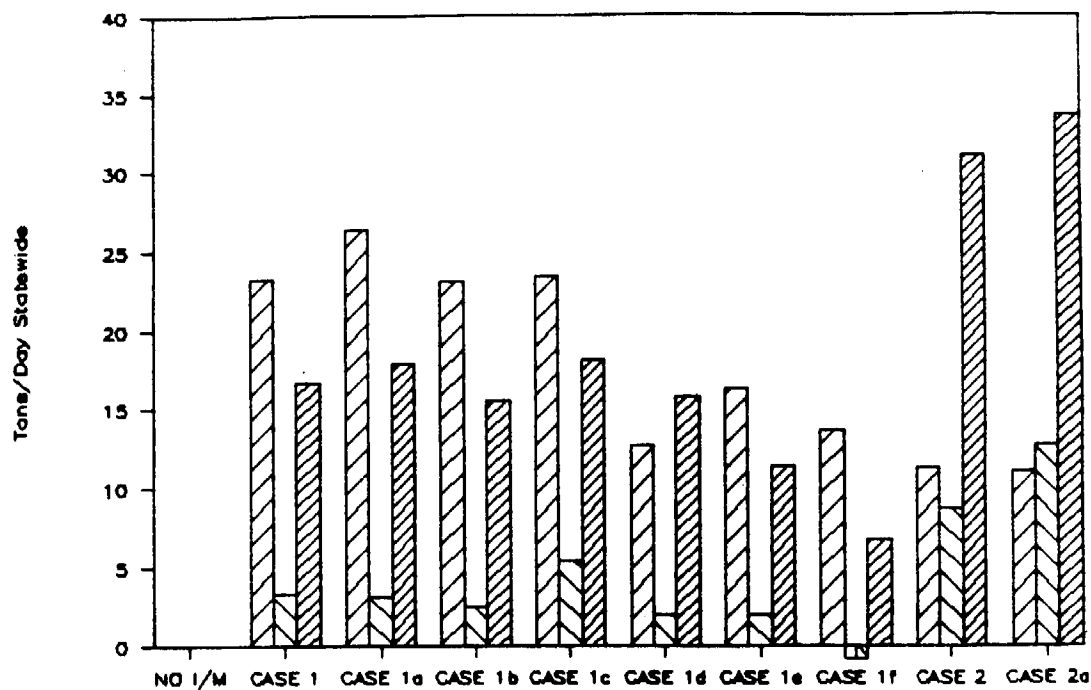


Figure ES-6: Emissions Reductions Projected for Alternative I&M Programs: 1990.

2000

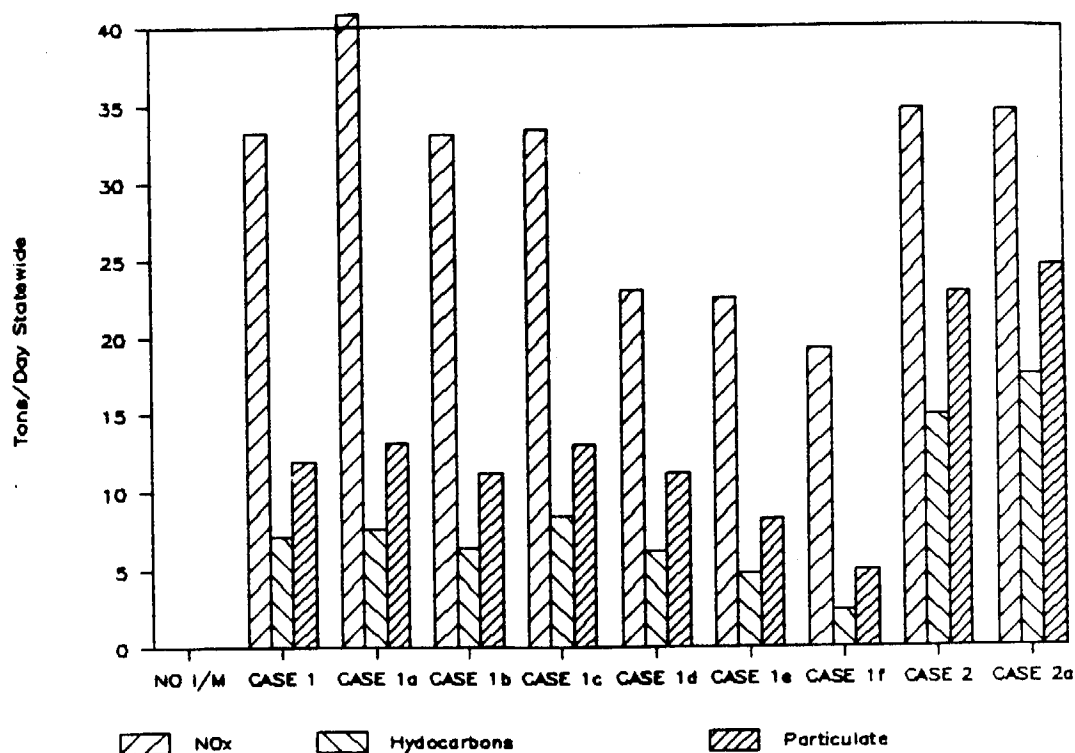


Figure ES-7: Emissions Reductions Projected for Alternative I&M Programs: 2000.

1990

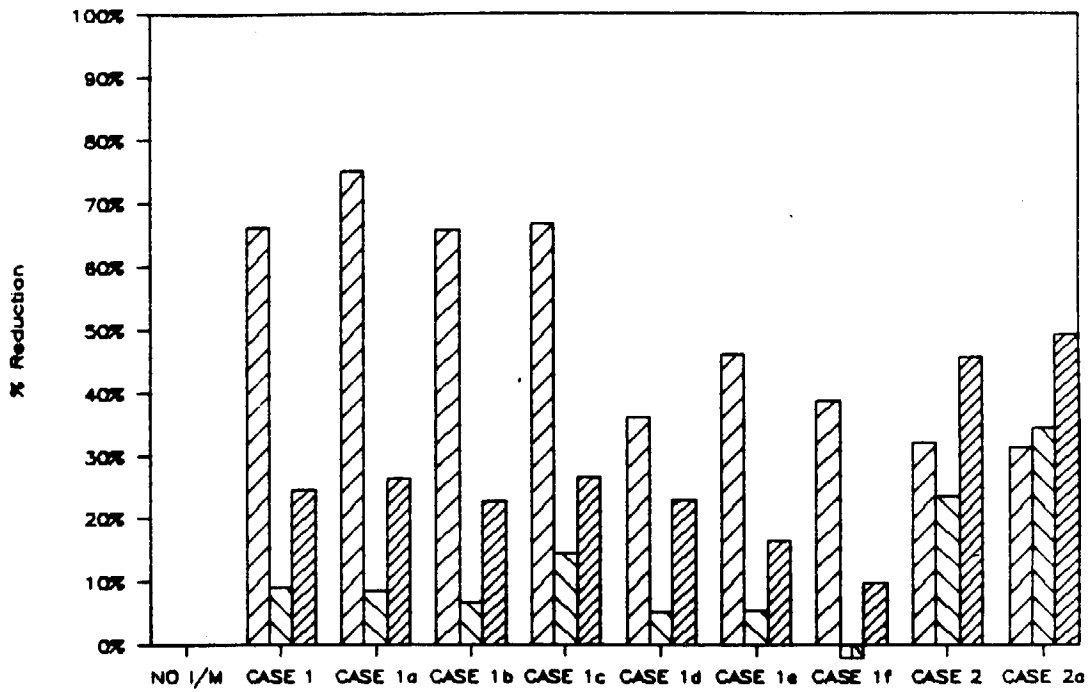


Figure ES-8: Percent Reduction in Excess Emissions for Alternative I&M Programs: 1990.

2000

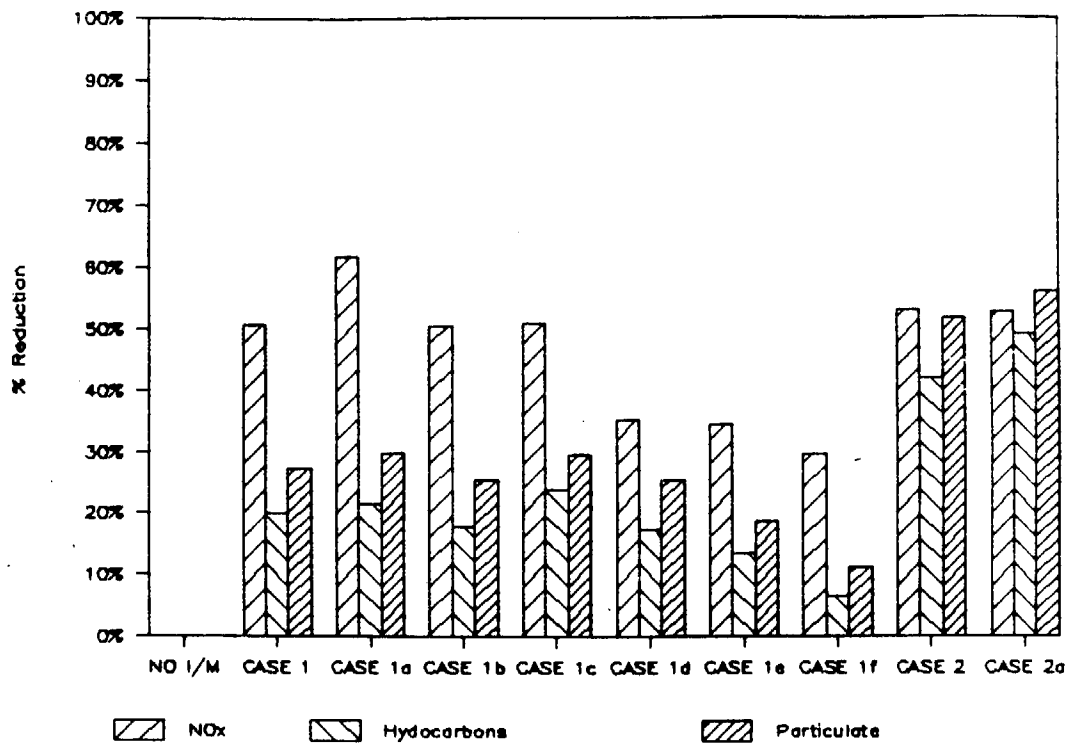


Figure ES-9: Percent Reduction in Excess Emissions for Alternative I&M Programs: 2000.

Program Costs: 1990

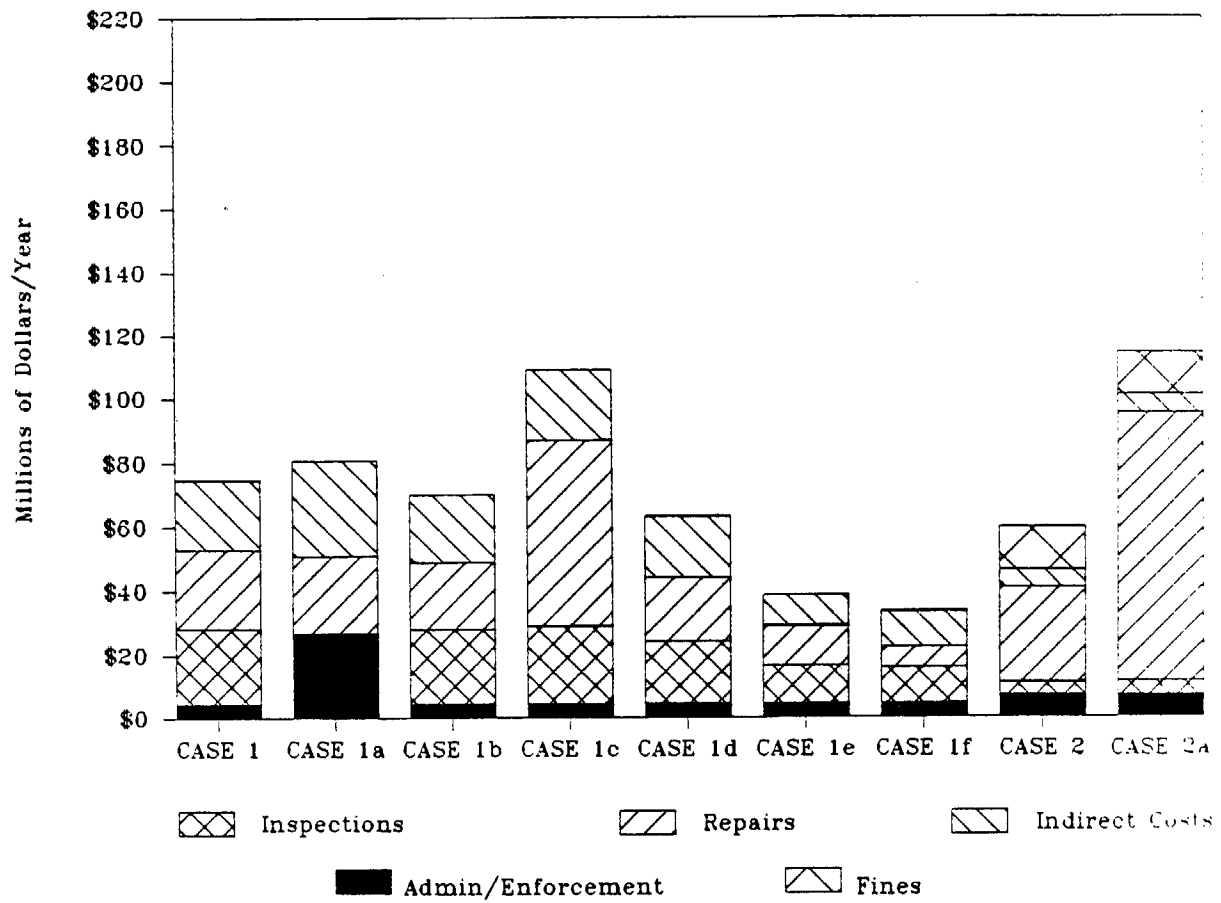


Figure ES-10: Estimated Costs of Alternative I&M Programs: 1990.

Program Costs: 2000

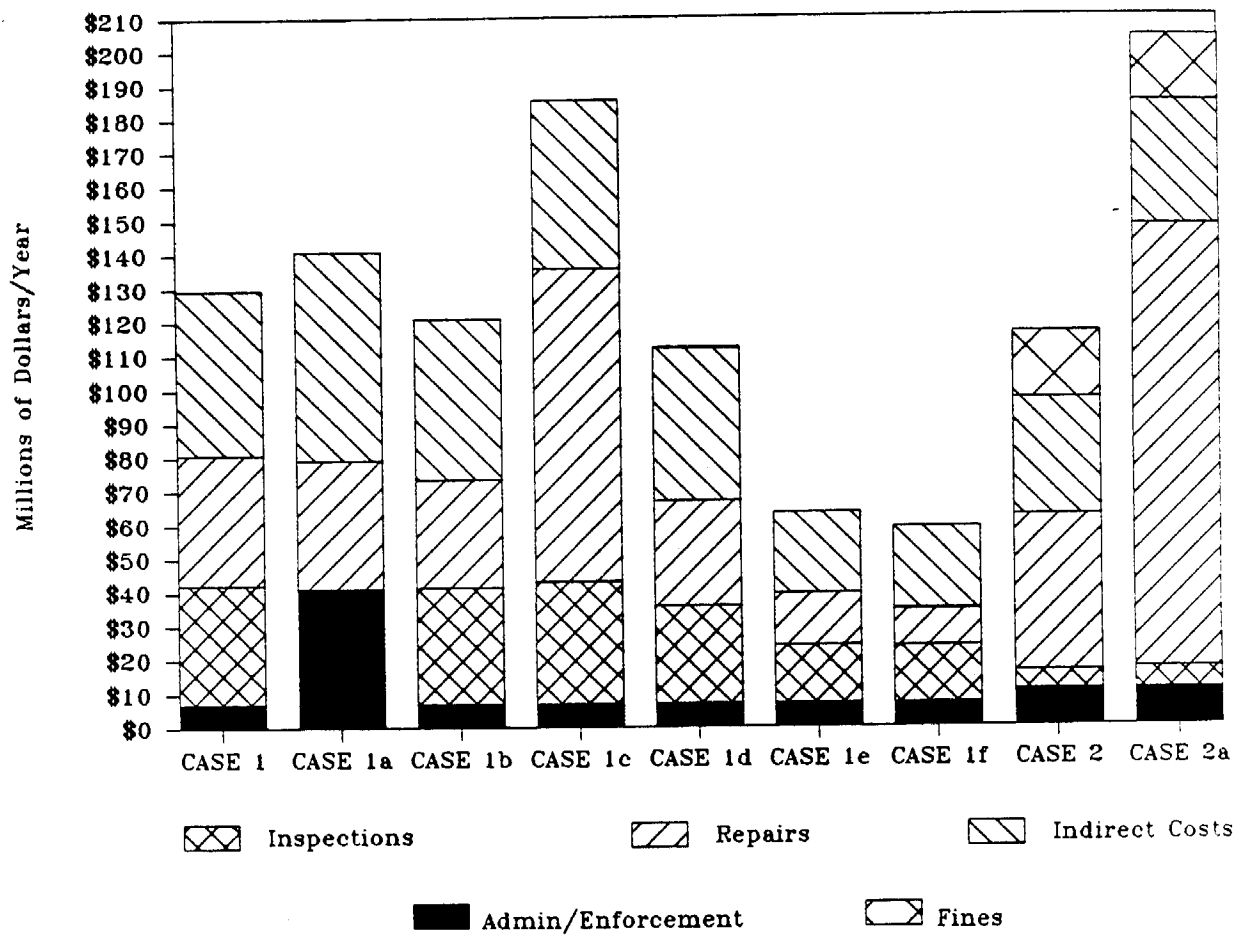


Figure ES-11: Estimated Costs of Alternative I&M Programs: 2000.

Cost-effectiveness estimates for each alternative are summarized in Figure 12. To calculate the cost-effectiveness of an emissions control strategy (such as I/M) which affects more than one pollutant requires that some decisions be made as to the proper allocation of costs between the different pollutants. For our calculations, we assigned each program a credit of \$4,000 per ton of  $\text{NO}_x$  or HC reduced, and assigned the remaining costs of the program to PM control. Making these assumptions, we were able to calculate the cost-effectiveness of each program as a particulate control measure, treating the HC and  $\text{NO}_x$  reductions as side benefits. The value of \$4,000 per ton of HC and  $\text{NO}_x$  eliminated is fairly typical of other ongoing emission control initiatives in California.

As Figure 12 shows, the most cost-effective I/M program scenario by our calculations is Case 2, followed by Case 1e. Cost-effectiveness estimates for Case 2 ranged from \$1,489/ton in 1990 to \$2,942/ton in 2000; those for Case 1e from \$2,836 to \$7,805. For comparison, the cost-effectiveness of the 1994 PM standard of 0.1 g/BHP-hr for heavy-duty vehicles has been estimated at around \$7,000-\$11,000 per ton of PM eliminated. Case 2 also results in the second largest reduction in emissions (after Case 2a), and thus appears clearly preferable overall.

By far the highest costs-per-ton of emissions control are calculated for the two scenarios with no repair cost limits, due to the very high costs of engine overhaul included in these cases. These calculations overestimate the actual economic costs somewhat, since overhauling an engine increases its value and useful life. Nonetheless, it appears that some reasonable limit on repair costs is needed in a heavy-duty diesel I/M program in order to keep overall program costs and cost-effectiveness reasonable.

#### CONCLUSIONS AND RECOMMENDATIONS

1. Malmaintenance and tampering with emissions controls are estimated to result in substantial excess emissions from heavy-duty diesel vehicles. Excess emissions will become even

Cost-Effectiveness for Particulate Control

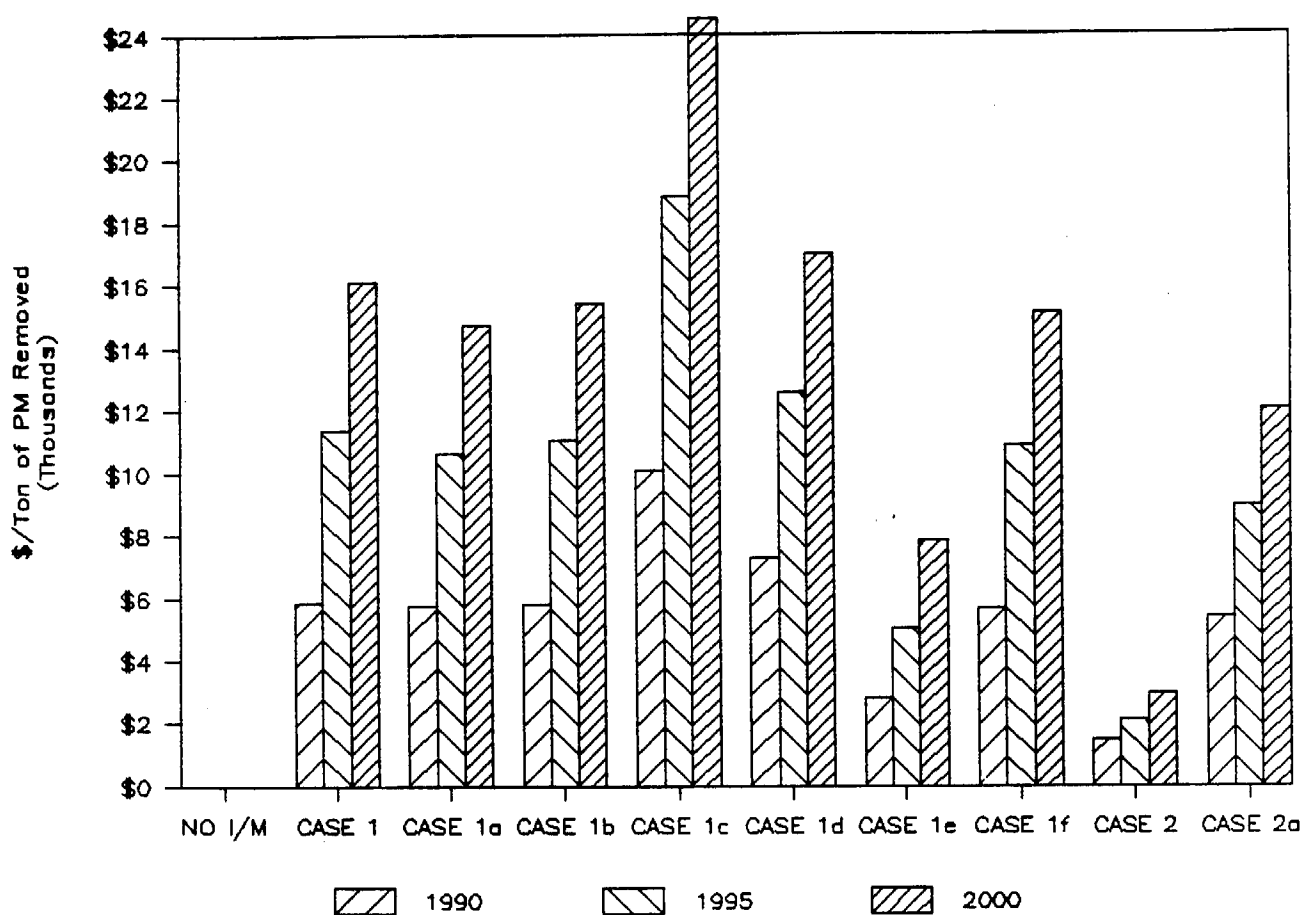


Figure ES-12: Estimated Cost-Effectiveness of Alternative I&M Programs For Particulate Emissions Control.

more significant in the future, as stringent new emissions controls introduce new motivations and opportunities for tampering.

2. A set of effective I/M test procedures for heavy-duty diesel trucks and buses has been developed and validated. These tests are able to identify about 65 to 80 percent of excess diesel PM and HC emissions.
3. Visual smoke monitoring at weigh stations (with confirmatory opacimeter testing) and random anti-tampering inspections in conjunction with existing safety checks would be the most effective and cost-effective I/M program for heavy-duty diesels. Periodic I/M programs such as the Smog Check are projected to be more expensive and less effective than an in-use program.
4. Due to the lack of an adequate statistical database, the estimates of excess emissions, I/M test effectiveness, and I/M program benefits developed in this study contain much uncertainty. It is recommended that ARB undertake a program for heavy-duty diesel vehicles which would be comparable to its periodic emissions surveillance programs for light-duty vehicles. This program should include recruitment of a representative sample of trucks and buses, and testing both for smoke opacity and for emissions using a heavy-duty transient test procedure.

## 1.0 INTRODUCTION

In order to protect and improve the quality of its air, the State of California is interested in minimizing pollutant emissions from heavy-duty diesel trucks and buses. Diesel-engined vehicles are major contributors to ambient levels of particulate matter and oxides of nitrogen ( $\text{NO}_x$ ) in urban air. Diesels also emit lesser (but still significant) amounts of unburned hydrocarbons (HC), and a small amount of carbon monoxide (CO). Diesel HC emissions are of special concern, since the hydrocarbon species emitted include polynuclear aromatic compounds, nitro-aromatics, and other toxic, carcinogenic, or mutagenic species. Diesel HC and aldehyde emissions are also responsible for the characteristic diesel odor.

New motor vehicles must meet strict pollutant emission standards before they can be sold. In order to improve the level of emissions control in customer use, however, California and many other states have found it necessary to implement programs of periodic inspection and maintenance (I/M) to check emissions levels and/or the functioning of emissions controls, and require corrective repairs where necessary. California presently has a strong I/M program for light-duty and some heavy-duty gasoline vehicles, and has considered a similar program for light-duty diesels. Heavy-duty vehicles--those over 8,500 pounds gross vehicle weight--have traditionally been exempted from I/M requirements, however. This is especially true for diesels.

Implementation of I/M programs for diesels has been impeded by the technical difficulty of developing a suitable emissions test, and by uncertainty as to the magnitude of the problem and of the cost-effectiveness of an I/M program for these vehicles. In response to the need for improved control of heavy-duty diesel emissions, the California Air Resources Board (ARB) contracted with Radian Corporation to quantify the problem of excess emissions from heavy-duty diesel trucks and buses, to develop preliminary I/M procedures for these vehicles, and to estimate the costs and cost-effectiveness of implementing an I/M program for heavy-duty diesels.

1.1 Outline of the Study

The project was divided into five major tasks, as listed below.

- (1) Quantify the problem of excess emissions from heavy-duty diesels due to poor maintenance and/or tampering with emission controls. This task included defining common emissions-related defects, estimating the frequency of defects in the truck population, estimating the emissions consequences of each defect, and combining these estimates with data on truck populations and travel patterns to estimate the impact of excess emissions from heavy-duty diesels on air quality and public offense due to excessive smoke.
- (2) Develop and document a periodic inspection procedure and a quick roadside smoke opacity check to identify heavy-duty diesel vehicles having excessive emissions. The periodic inspection procedure was intended to be conceptually similar to the procedures for the present Smog Check Program for light-duty gasoline vehicles. The roadside opacity check procedure was intended as a quick and simple check for excessive emissions which could be applied at a truck weigh station or similar environment.
- (3) Estimate the costs and emissions benefits of implementing the procedures developed in Task Two, assuming that the emissions defects identified by the procedure are properly repaired.
- (4) Validate the procedures developed in Task Two by applying them to a representative sample of trucks in a blind test.
- (5) Prepare a final report documenting the work.

## 1.2 Outline of the Report

The final report for this project is contained in four volumes, of which this is Volume I. The volume numbers and their titles are as follows:

- I. SUMMARY REPORT
- II. QUANTIFYING THE PROBLEM
- III. DEVELOPMENT AND VALIDATION OF I/M TEST PROCEDURES
- IV. I/M PROGRAM DESIGN AND COST-EFFECTIVENESS ANALYSIS

Volume I, this volume, presents an overview of the other three volumes, and summarizes the major conclusions and recommendations. Volume II describes a computer model of heavy-duty diesel emissions developed for this project, and presents the model results for the case with no I/M program. Volume III describes the development and validation of test procedures to identify heavy-duty diesel vehicles which are excess emitters. Volume IV outlines several possible designs for I/M programs using these procedures, and estimates the emissions reductions and cost-effectiveness for each.

## 1.3 Limitations and Caveats

This report presents our estimates of the current and future pollutant emissions from heavy-duty diesel vehicles in California; and the effectiveness, costs, and cost-effectiveness of each of several possible heavy-duty diesel I/M programs. These estimates are heavily based on the model of excess heavy-duty diesel emissions described in Volume II, and the I/M effects model described in Volume IV. Neither these models nor any other can produce "Truth"; at best, they can only reflect the consequences of the data and assumptions that go into them. The limitations on the data and assumptions going into these models are discussed in Volumes II and IV.

The results presented here reflect our estimates of the effects of alternative heavy-duty diesel I/M programs. These estimates are necessarily very rough: estimates of the effectiveness even of operating I/M programs are notoriously difficult, and no programs comparable to those described here are now in operation. In the absence of hard data to serve as a benchmark, even the most careful estimates contain a great deal of uncertainty, and the ones presented here should be understood in this light. Our estimates are based on experienced judgement, and we consider them to be somewhat conservative (in the sense of under-estimating the effects of an I/M program), but they cannot be shown to be either "right" or "wrong" based on the data available today.

Our estimates also assume that the programs described are competently designed, effectively executed, and vigorously enforced. This has not always been the case in light-duty I/M programs in the U.S. A poorly designed, mismanaged, or badly enforced I/M program would sacrifice a large portion of the benefits estimated in this report, while costing as much or more. These limitations should also be borne in mind in interpreting and applying our results.

## 2.0        QUANTIFYING THE PROBLEM OF EXCESS EMISSIONS FROM HEAVY-DUTY DIESEL VEHICLES

In Task 1 of this study, Radian developed a computer model of total and excess emissions from heavy-duty diesel vehicles. This model, its input data, and the model results are described in detail in Volume II, and briefly summarized below.

### 2.1        Frequency of Occurrence of Emissions-Related Defects

Table 2-1 is a list of common types of tampering and malmaintenance-related defects which can affect emissions from heavy-duty diesel vehicles. Virtually no reliable published information on the frequency of occurrence of these defects in heavy-duty vehicles exists. In order to fill this gap in the available data, we undertook two surveys as part of this program. The first was a field survey of truck smoke emissions, using visual observation. The second was a questionnaire survey of truck mechanics, engine rebuilders, and fleet maintenance managers, undertaken as part of a larger study of engine rebuilding practices by another ARB contractor.

Visual smoke survey--Most of the more common types of emissions-related defects show a characteristic smoke emissions "signature". Smoke emissions in different operating modes are different for different types of defects. For example, tampering with the smoke limiter on a turbocharged engine results in excess smoke during acceleration, but has no effect on steady-state smoke. It is thus possible to estimate the frequency of occurrence of many types of emissions-related defects by comparing the frequency and severity of smoke emissions data from different operating modes.

To obtain first-hand information on diesel truck smoke emissions patterns, a visual survey of truck smoke emissions in California was undertaken. Truck smoke emissions were observed visually by a Radian staff member who had been ARB-certified as a smoke reader. Trucks were observed in three operating modes: acceleration from low speed or stop, steady-state full-power

TABLE 2-1. COMMON TYPES OF EMISSIONS-RELATED DEFECTS  
IN HEAVY-DUTY DIESEL TRUCKS

Defect	Likely Cause
<u>Injection Timing Changes</u>	
Timing Retarded	Wear/Malmaintenance
Timing Advanced	Tampering/Malmaintenance
<u>Fuel Injection Problems</u>	
Minor Injector Problem	Wear
Moderate Injector Problem	Wear
Severe Injector Problem	Wear/Bad Fuel
<u>Fuel Air Ratio Problems</u>	
Puff Limiter Misset	Tampering/Malmaintenance
Puff Limiter Disabled	Tampering
Maximum Fuel Too High	Tampering
Clogged Air Filter	Malmaintenance
Turbocharger Worn	Wear
Turbocharger Wrong Type	Tampering
Intercooler Clogged	Malmaintenance
Other Air-Supply Problems	Malmaintenance
<u>Other Engine Problems</u>	
Improper Rebuilding	Tampering/Malmaintenance
Excessive Oil Consumption	Wear
Engine Mechanical Failure	Malmaintenance
<u>Future Technologies</u>	
Electronic Controls Failed	Malmaintenance
Electronic Controls Tampered	Tampering
Catalytic Converter Removed	Tampering
Trap Bypassed	Tampering
Trap Failed/Removed	Tampering
EGR System Disabled	Tampering

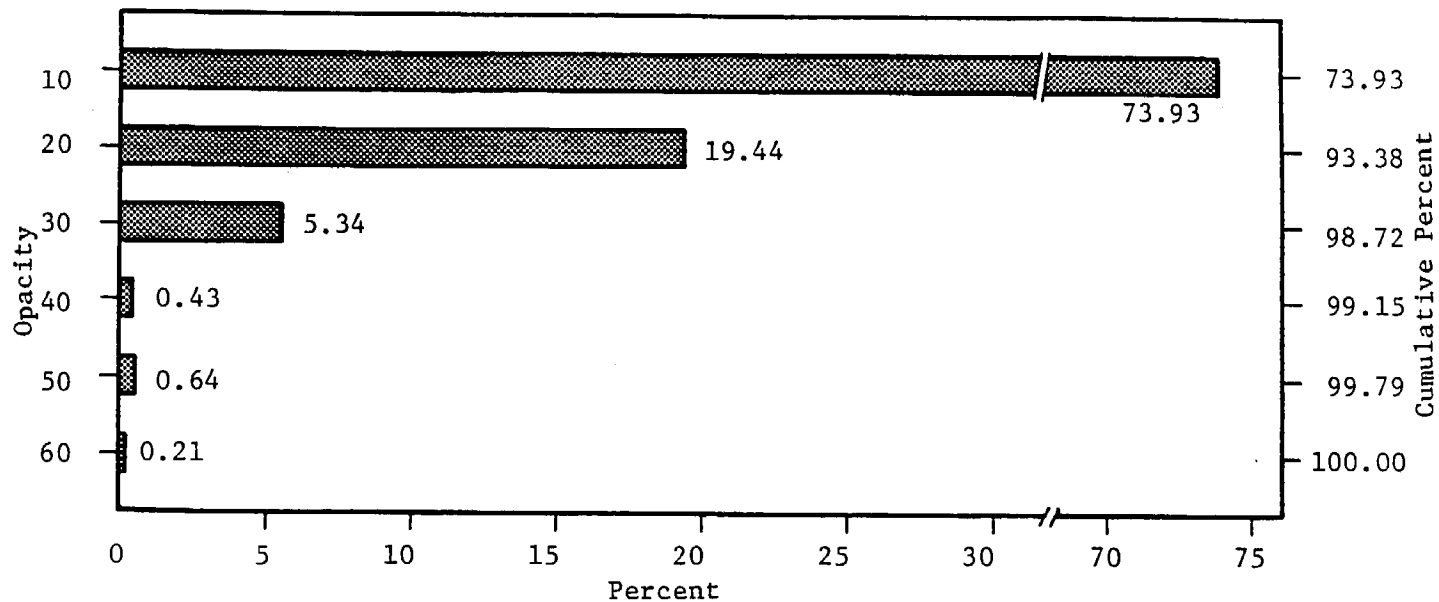
operation (up a steep hill), and steady-state road-load operation on a level section of freeway.

Observations were made at a number of sites in the Los Angeles and Oakland/Sacramento areas; in all, 1,243 observations at 13 locations were recorded. An attempt was made to observe a representative cross-section of the trucking activity in the State (e.g. long-distance and interstate trucking on I-80, short-distance trucking on L.A.'s Harbor Freeway and the L.A. Harbor area).

Figures 2-1 through 2-3 summarize the results of the truck smoke survey. Figure 2-1 shows the distribution of smoke opacities observed for trucks in steady-state, road-load operation, Figure 2-2 shows the opacity distribution for steady-state, full-load operation, and Figure 2-3 shows the distribution for transient smoke during acceleration.

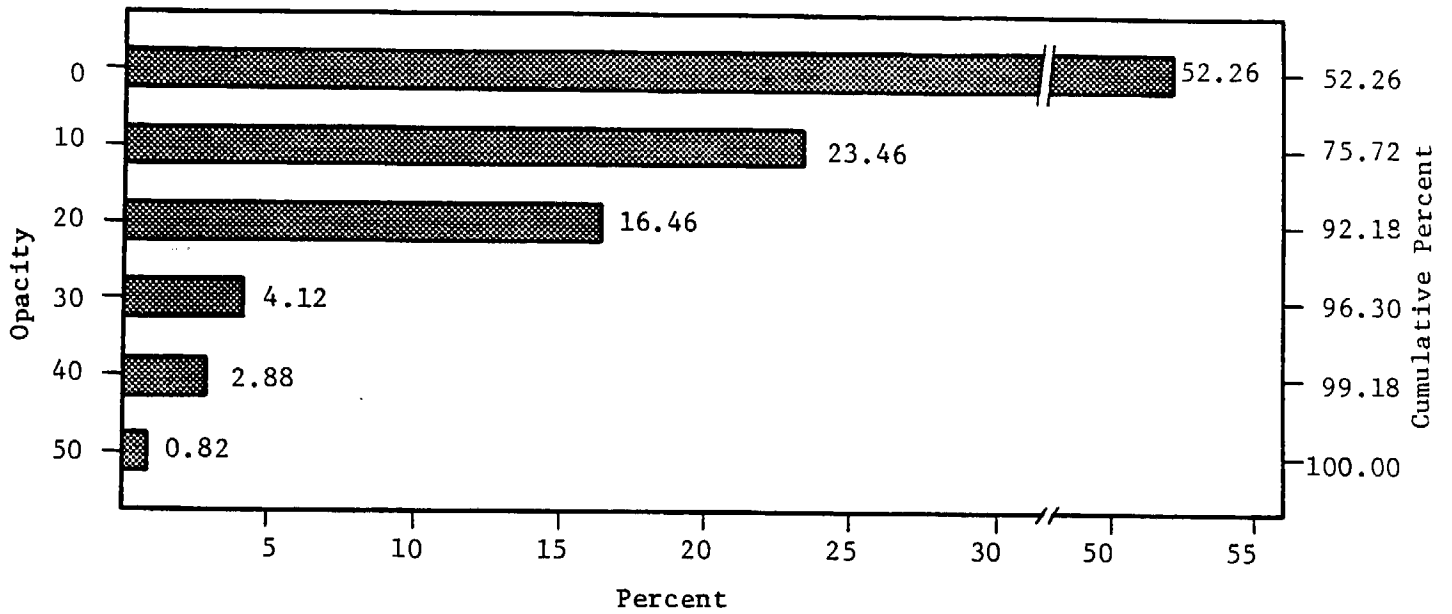
As these figures indicate, both the greatest range in values and the highest absolute values for opacity are found in the acceleration mode. Roughly half of the trucks observed had peak acceleration smoke opacities less than 30 percent (slight to moderate smoke). Most of the rest (44 percent of the total) had opacities in the 40 to 60 percent range. Most people would consider this smoke level to be visually offensive. The remaining 6 percent had opacities over 60 percent, indicating very heavy (and highly offensive) smoke. As expected, smoke emissions in steady-state, full-power operation were much lower, and those in road-load operation lower still.

The significance of these smoke data can be understood by comparing them to the results for well-maintained engines. Federal smoke regulations limit smoke opacity in peak, acceleration average, and lug-down modes to 50 percent, 20 percent, and 15 percent, respectively. Our observations of acceleration smoke are most comparable to the peak value, although we would expect them to be somewhat lower due to the eye's tendency to "average" rapid changes in opacity. Our full-power observations are comparable to the



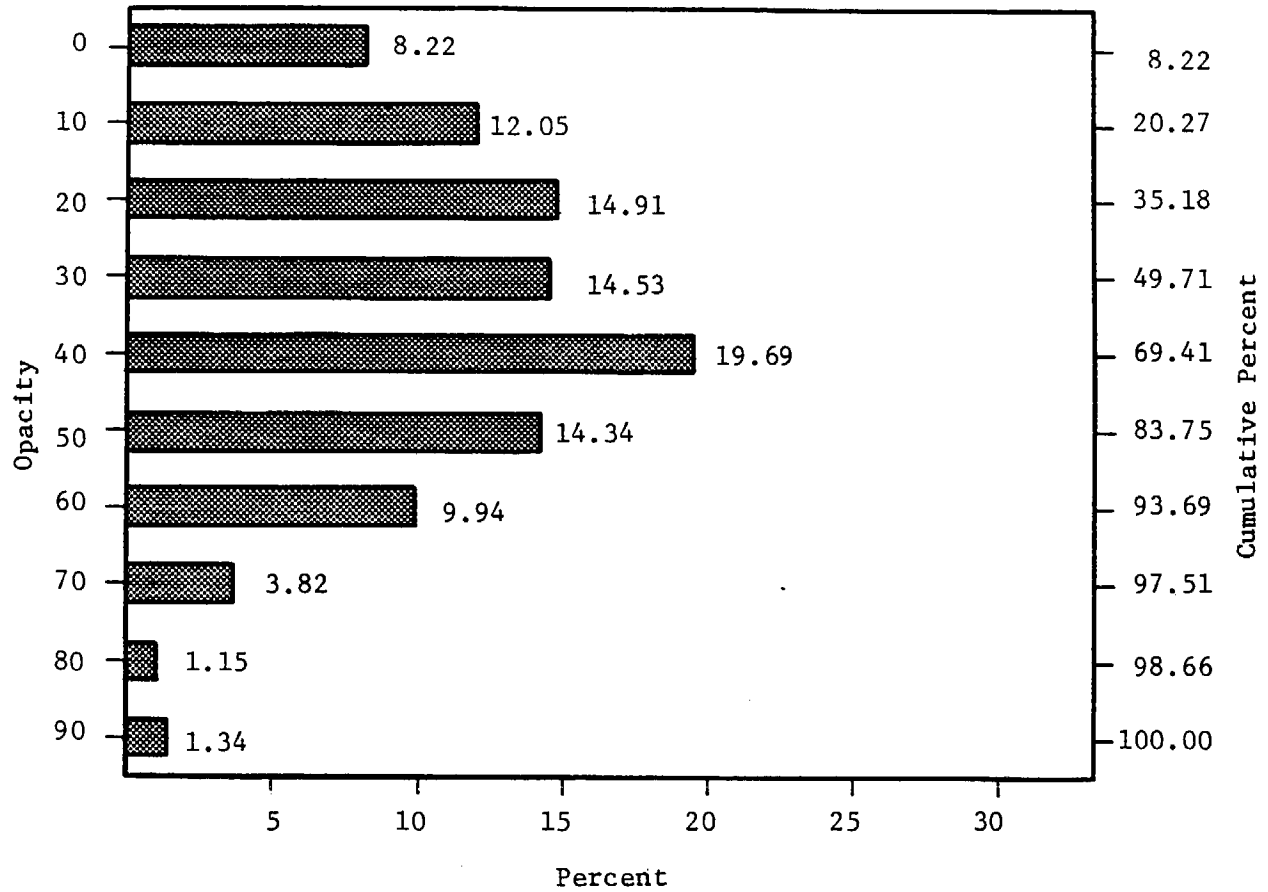
Sample size = 468

Figure 2-1. Distribution of Truck Smoke Opacity  
in Road-Load Operation



Sample size = 243

Figure 2-2. Distribution of Truck Smoke Opacity in Full-Power, Steady-State Operation



Sample size = 523

Figure 2-3. Distribution of Truck Smoke Opacity Under Transient Acceleration

"lug-down" value, although again, we would expect them to be somewhat lower. The lug-down value measures smoke opacity at near the peak torque point, while most of the engines we observed would have been operating at higher engine speeds where smoke emissions are lower.

Based on Federal smoke certification data, peak smoke levels of about 20 to 30 percent opacity should be typical of well-maintained and properly adjusted engines, while a typical lug-down smoke level would be about 10 percent. Only 10 of 153 heavy-duty diesel engines certified in 1987 had peak smoke opacities greater than 35 percent, and most of these were smaller, naturally aspirated engines used in light and medium-heavy duty trucks, not the heavy-heavy trucks in our survey. Only two engine families in 1987 certified with peak opacities of 40 percent or more; in 1986, only one did. In our visual survey, however, slightly more than half the trucks were estimated to have peak smoke opacities of 40 percent or more.

The cruise mode in our observations has no counterpart in the Federal smoke tests, since this operating mode should not normally produce visible smoke. Smoke opacity in this part-load, steady-state cruise mode is normally 2 percent or less in a properly functioning engine. Our visual survey showed more than 25 percent of the trucks observed with opacities of 10 percent or more, however. Clearly, a large fraction of trucks on the road in California are emitting excessive smoke.

Maintenance questionnaire--Experienced professional mechanics and other engine professionals would be expected to have reasonably good knowledge of the state of maintenance of the "average truck". Where hard statistical data are lacking, the consensus of those directly involved in the field may be a useful guide; this is the foundation of the so-called "Delphi" method. In order to obtain these professionals' estimates of the frequency of various emissions-related defects, Radian prepared a set of questions to be included in a survey of diesel engine mechanics and rebuilders that was being conducted by another ARB contractor. A total of 103 responses were received to this

survey. The respondents were asked to estimate (or give their best guess at) the fraction of all trucks on the road which exhibit each of a number of common types of problems.

This wording represented a compromise. From the standpoint of survey response and reliability, it would have been preferable to ask about the incidence of problems in the particular group of trucks that each respondent was responsible for, since respondents could then have answered from their own knowledge rather than from their (possibly less reliable) impressions of the industry as a whole. On the other hand, the survey was planned to target fleet maintenance managers and heavy-duty truck mechanics. Asking about only the vehicles each was responsible for would have biased the estimates downward, since the very existence of a fleet maintenance manager implies a significant commitment to proper maintenance, and the worst-maintained vehicles probably seldom see the inside of a truck repair shop. In addition, many of the practices asked about are illegal, and it was considered likely that respondents would be unwilling to admit to engaging in illegal acts.

A statistical summary of the survey results is given in Table 2-2. The minimum, maximum, and median responses, the sample mean, and the upper and lower confidence limits (at the 68 percent significance level) for the mean are shown for each question. These data tend to confirm the impressions developed from the visual smoke survey and from anecdotal evidence. Resetting and disabling smoke limiters, increasing maximum fuel settings, and advancing the injection timing are considered to be quite common, especially on line-haul trucks. The most common maintenance problems are worn or clogged injectors and clogged air filters, followed by worn turbochargers and pressure leaks. Clogged intercoolers and excessive backpressure are considered less common, but by no means rare.

TABLE. 2-2. SURVEY OF DIESEL MECHANICS AND MAINTENANCE MANAGERS:  
 QUESTIONNAIRE RESULTS

Question	Minimum	Lower Con. Limit	Sample Mean	Upper Con. Limit	Maximum	Median
1. Injection Timing Advanced						
Line Haul	0	11.1	12.4	13.8	50	10
Other Turbocharged	0	7.3	8.6	9.9	50	5
Nat. Aspirated	0	9.8	11.7	13.5	75	10
2. Injection Timing Retarded						
Line Haul	0	6.5	7.6	8.6	30	5
Other Turbocharged	0	5.6	5.8	8.1	40	2
Nat. Aspirated	0	5.1	6.2	7.3	45	3
3. Injectors-Worn or Clogged						
Line Haul	0	17.8	20.0	22.1	75	15
Other Turbocharged	0	18.9	21.1	23.2	75	15
Nat. Aspirated	0	20.1	22.4	24.6	75	20
4. Smoke-Limiter Reset						
Line Haul	0	25.8	28.8	31.9	100	20
Other Turbocharged	0	15.2	17.7	20.3	80	10
5. Smoke-Limiter Disabled						
Line Haul	0	26.8	29.8	32.9	100	25
Other Turbocharged	0	15.0	17.4	19.8	80	10
6. Maximum Fuel "Turned Up"						
Line Haul	0	21.8	23.7	25.7	80	20
Other Turbocharged	0	12.3	14.1	15.9	80	10
Nat. Aspirated	0	15.1	17.2	19.3	90	10
7. Air Filter Clogged						
Line Haul	0	20.0	21.9	23.9	80	20
Other Turbocharged	0	21.1	23.2	25.3	65	20
Nat. Aspirated	0	19.0	21.0	23.1	60	18
8. Intercooler Clogged						
Line Haul	0	5.9	7.0	8.0	60	5
Other Turbocharged	0	3.4	4.1	4.9	20	1
9. Turbocharger Worn						
Line Haul	0	12.3	13.7	15.2	80	10
Other Turbocharged	0	11.6	13.2	14.8	80	10
10. Nonstandard Turbocharger						
Line Haul	0	7.5	8.7	9.9	50	5
Other Turbocharged	0	5.0	5.8	6.6	25	5
11. Pressure Leaks						
Line Haul	0	11.6	12.8	14.0	50	10
Other Turbocharged	0	10.5	11.9	13.3	60	10
12. Excessive Backpressure						
Line Haul	0	5.3	6.5	7.7	15	5
Other Turbocharged	0	5.6	6.9	8.2	15	10
Nat. Aspirated	0	6.2	8.4	10.7	25	10

Total Responses: 103

## 2.2 Emissions Impacts of Tampering and Malmaintenance

To estimate the overall emissions impacts of tampering and mal-maintenance in diesel engines, a computer model of diesel emissions and tampering/malmaintenance effects was constructed. This model deals with four general classes of heavy-duty diesel vehicles: heavy-heavy, medium-heavy, light-heavy, and transit bus. The model further differentiates between out-of-state and California-registered vehicles, and between California-registered vehicles with California and Federal engines. Input data to this model included estimates of the baseline emissions for each heavy-duty vehicle class and model year, and the frequencies of occurrence and the emissions impacts of individual defects. This model is described extensively in Volume II.

The emissions model results for the case with no I/M program are plotted in Figures 2-4 through 2-6. These figures display the total annual average statewide emissions of  $\text{NO}_x$ , unburned hydrocarbons, and diesel particulate matter from heavy-duty diesel vehicles, expressed in tons of pollution per day. These projections are broken down into baseline emissions and excess emissions. The baseline emissions level is the amount of pollution that would be emitted even if all the engines in use were in good mechanical condition with their emission controls performing properly. Excess emissions are defined as the increase over and above the baseline emissions level due to tampering, malmaintenance, and excessive engine wear.

As Figures 2-4 through 2-6 show, excess emissions are estimated to account for a large and increasing fraction of HC and PM emissions. Excess  $\text{NO}_x$  emissions are estimated to be a smaller fraction of the total. Because heavy-duty diesel  $\text{NO}_x$  emissions are so large, however, this excess is still significant for air quality.

The emissions estimates developed in this study are considerably higher than current ARB estimates and projections. This is due to the higher

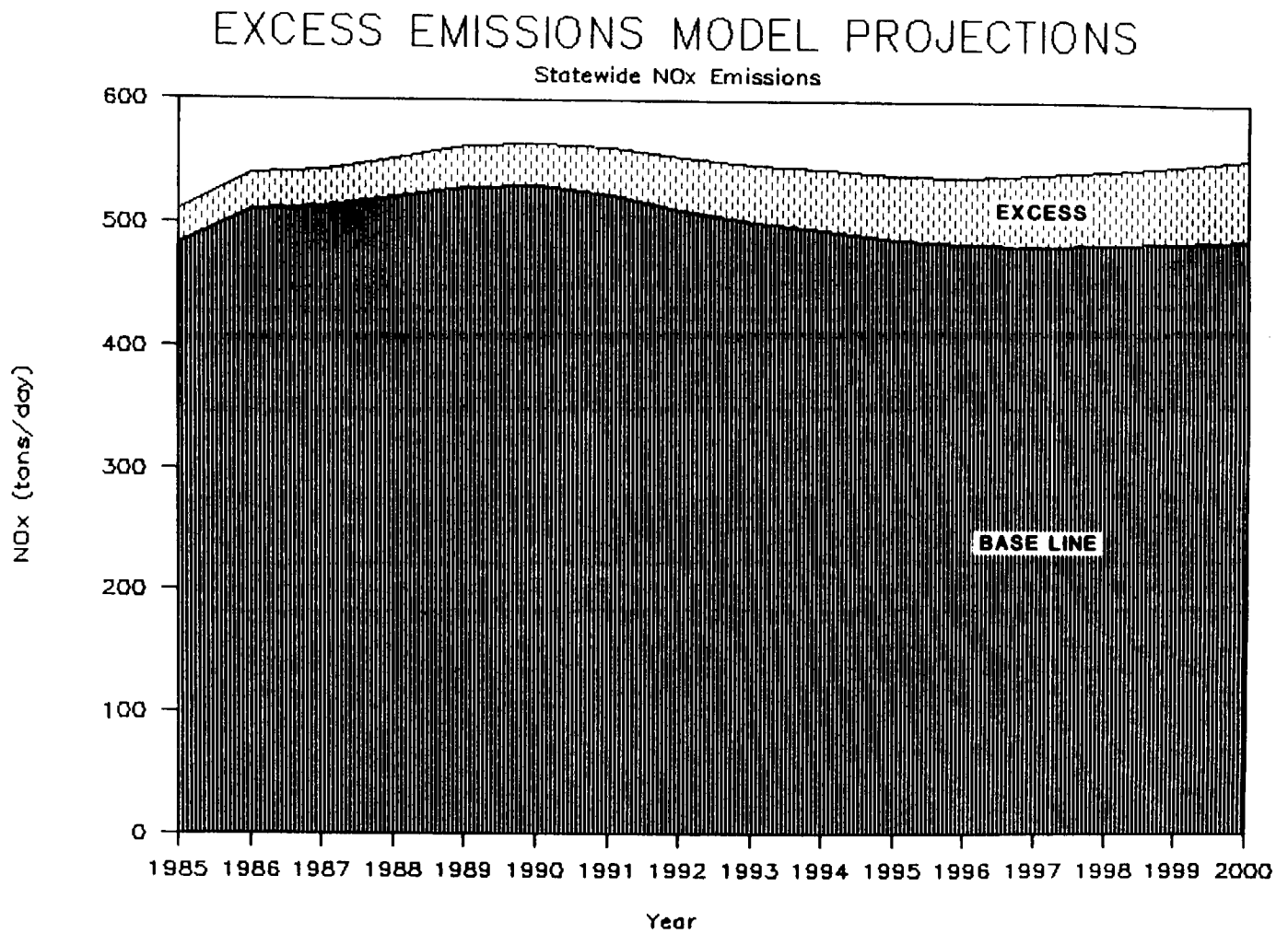


Figure 2-4. Projected Statewide NO<sub>x</sub> Emissions from Heavy-Duty Vehicles

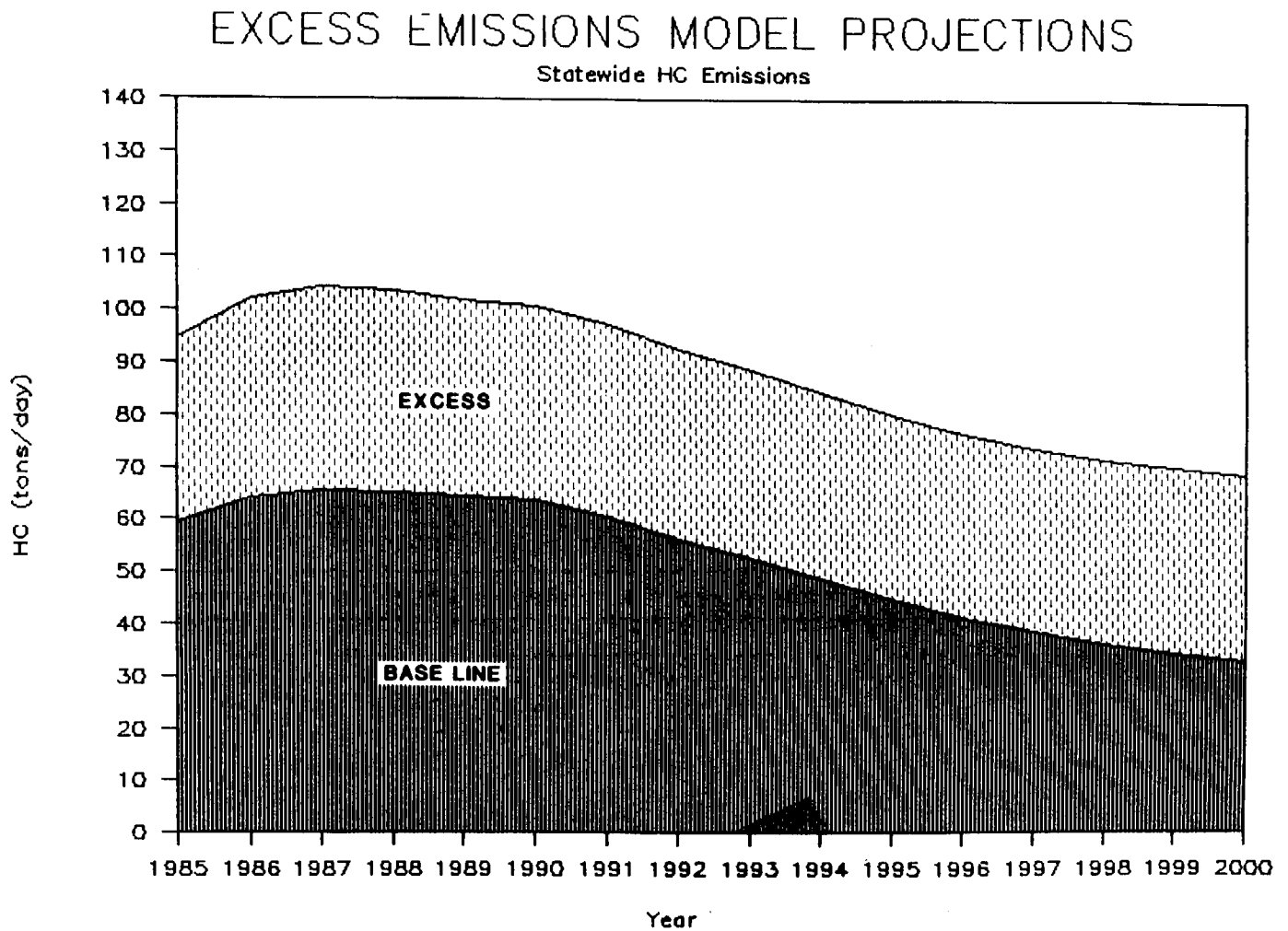


Figure 2-5. Projected Statewide HC Emissions from Heavy-Duty Diesel Vehicles

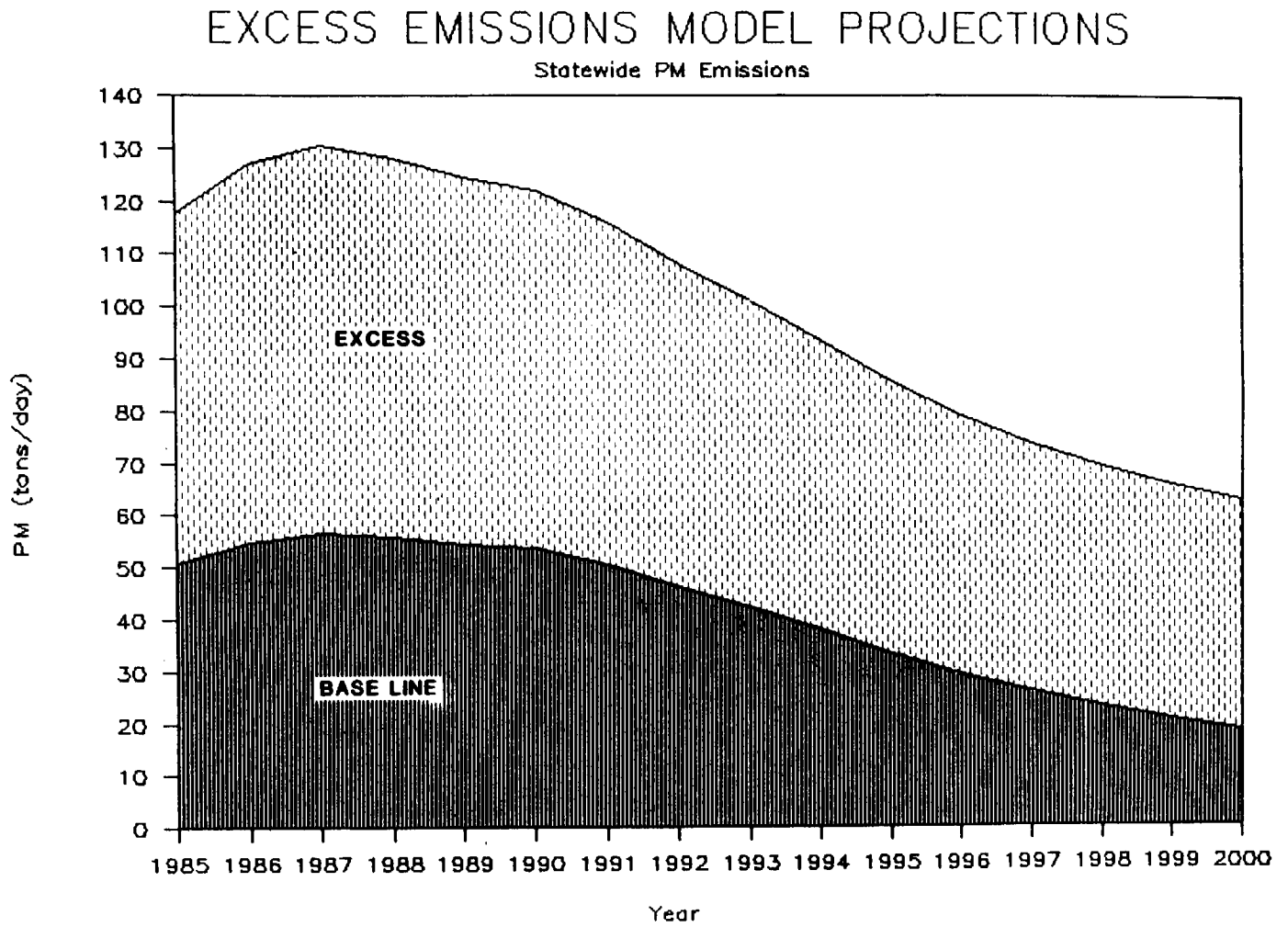


Figure 2-6. Projected Statewide PM Emissions from Heavy-Duty Diesel Vehicles

emission factors (grams of pollutant per vehicle-mile travelled) estimated in this study. Table 2-3 compares Radian's estimates of fleet-average emission factors in several years with those projected by EMFAC7C. The higher Radian values for PM are due primarily to the greater in-use deterioration projected in this study. The higher  $\text{NO}_x$  values are also partly due to the large number of Federally-certified trucks and buses projected to be used in California.

Tables 2-4 and 2-5 show the breakdown of total and excess pollutant emissions between the different classes of heavy-duty vehicles treated in the model. As these tables indicate, the lion's share of both total and excess emissions are due to heavy-heavy and medium-heavy trucks; light-heavy duty vehicles and transit buses are responsible for a relatively minor share. Out-of-state vehicles (which are assumed to have Federal engines) are fairly significant contributors to the overall emissions levels, but California-registered vehicles with Federal engines are even more significant. Together, these groups account for about half of the total heavy-duty diesel emissions in California.

Because of the lack of applicable statistical data to base them on, the model projections presented in here contain considerable uncertainty. The range of uncertainty in the excess emissions estimates is estimated at -30 percent to +70 percent of the value shown, while the uncertainty in the total emissions is estimated at approximately -20 to +50 percent.

TABLE 2-3. COMPARISON OF RADIAN FLEET-AVERAGE EMISSION  
FACTOR ESTIMATES WITH EMFAC7C

Calendar Year	EMFAC7C <sup>1</sup>	Radian Average of All Classes
<u>1985</u>		
NOx	19.52	22.6
HC	3.02	4.2
PM	2.63	5.2
<u>1990</u>		
NOx	16.90	19.3
HC	2.72	3.4
PM	2.35	4.2
<u>1995</u>		
NOx	15.82	16.3
HC	2.61	2.4
PM	1.66	2.6
<u>2000</u>		
NOx	13.46	15.0
HC	2.51	1.8
PM	1.29	1.7

<sup>1</sup> Source: EMFAC7C pred. for California, April 6, 1986.

TABLE 2-4. CONTRIBUTIONS OF EACH HEAVY-DUTY CLASS  
 TO TOTAL STATEWIDE EMISSIONS

---



---

CONTRIBUTIONS TO TOTAL STATEWIDE EMISSIONS: 1987						
	<u>California Registered</u>			<u>Out-Of-</u>		
	<u>Calif.</u>	<u>Federal</u>	<u>Total</u>	<u>State</u>	<u>Total</u>	<u>Percent</u>
	<u>Engine</u>	<u>Engine</u>		<u>Vehicles</u>		
<u>Oxides of Nitrogen (TPD)</u>						
Heavy	111.7	133.7	245.4	92.5	337.9	62.3%
Medium	87.2	30.8	118.0	41.6	159.6	29.4%
Light	4.9	0.6	5.4	0.2	5.6	1.0%
Bus	16.9	22.7	39.6	0.0	39.6	7.3%
Total	220.7	187.7	408.4	134.3	542.7	100.0%
Percent	40.7%	34.6%	75.3%	24.7%	100.0%	
<u>Unburned Hydrocarbons (TPD)</u>						
Heavy	23.0	21.4	44.4	12.9	57.3	54.9%
Medium	24.3	6.4	30.8	8.6	39.4	37.7%
Light	1.6	0.2	1.8	0.1	1.8	1.7%
Bus	4.1	1.9	5.9	0.0	5.9	5.7%
Total	53.0	29.9	82.9	21.6	104.5	100.0%
Percent	50.7%	28.7%	79.4%	20.6%	100.0%	
<u>Particulate Matter (TPD)</u>						
Heavy	36.0	29.3	65.3	17.4	82.7	63.2%
Medium	27.3	6.5	33.9	8.8	42.6	32.6%
Light	1.3	0.2	1.4	0.0	1.5	1.1%
Bus	2.8	1.2	4.0	0.0	4.0	3.0%
Total	67.4	37.2	104.6	26.2	130.8	100.0%
Percent	51.5%	28.4%	80.0%	20.0%	100.0%	

---

(Continued)

TABLE 2-4. (Continued)

## CONTRIBUTIONS TO TOTAL STATEWIDE EMISSIONS: 2000

	<u>California Registered</u>			<u>Out-Of-</u>		
	<u>Calif.</u>	<u>Federal</u>	<u>Total</u>	<u>State</u>	<u>Total</u>	<u>Percent</u>
	<u>Engine</u>	<u>Engine</u>		<u>Vehicles</u>		
<u>Oxides of Nitrogen (TPD)</u>						
Heavy	128.6	137.1	265.8	87.6	353.4	63.6%
Medium	97.1	26.7	123.8	33.4	157.2	28.3%
Light	14.2	1.8	16.0	0.5	16.5	3.0%
Bus	12.8	15.4	28.2	0.0	28.2	5.1%
Total	252.8	181.0	433.7	121.5	555.3	100.0%
Percent	45.5%	32.6%	78.1%	21.9%	100.0%	
<u>Unburned Hydrocarbons (TPD)</u>						
Heavy	14.9	13.8	28.7	7.3	36.1	52.6%
Medium	16.5	4.4	20.8	5.4	26.3	38.3%
Light	2.6	0.3	2.9	0.1	3.0	4.4%
Bus	2.2	1.0	3.3	0.0	3.3	4.8%
Total	36.2	19.5	55.8	12.8	68.6	100.0%
Percent	52.8%	28.5%	81.3%	18.7%	100.0%	
<u>Particulate Matter (TPD)</u>						
Heavy	16.8	15.2	32.0	7.8	39.9	63.5%
Medium	12.1	3.1	15.3	3.9	19.2	30.6%
Light	1.9	0.2	2.1	0.1	2.1	3.4%
Bus	1.1	0.5	1.6	0.0	1.6	2.5%
Total	31.9	19.1	50.9	11.8	62.8	100.0%
Percent	50.8%	30.4%	81.2%	18.8%	100.0%	

TABLE 2-5. CONTRIBUTIONS OF TOTAL EXCESS EMISSIONS BY  
EACH HEAVY-DUTY VEHICLE CLASS

CONTRIBUTIONS TO STATEWIDE EXCESS EMISSIONS: 1987

	<u>California Registered</u>			<u>Out-Of-</u>		
	<u>Calif.</u>	<u>Federal</u>	<u>Total</u>	<u>State</u>	<u>Total</u>	<u>Percent</u>
	<u>Engine</u>	<u>Engine</u>		<u>Vehicles</u>		
<u>Oxides of Nitrogen (TPD)</u>						
Heavy	10.7	3.5	14.3	2.8	17.1	59.8%
Medium	7.6	1.1	8.7	1.6	10.3	36.1%
Light	0.0	0.0	0.0	0.0	0.0	0.0%
Bus	1.1	0.1	1.2	0.0	1.2	4.1%
Total	19.4	4.7	24.2	4.4	28.5	100.0%
Percent	68.0%	16.6%	84.6%	15.4%	100.0%	
<u>Unburned Hydrocarbons (TPD)</u>						
Heavy	8.8	7.3	16.1	3.1	19.2	49.6%
Medium	10.5	2.8	13.2	3.6	16.9	43.5%
Light	0.7	0.1	0.8	0.0	0.8	2.1%
Bus	1.3	0.6	1.9	0.0	1.9	4.8%
Total	21.3	10.7	32.0	6.8	38.8	100.0%
Percent	55.0%	27.5%	82.5%	17.5%	100.0%	
<u>Particulate Matter (TPD)</u>						
Heavy	21.8	16.9	38.7	8.8	47.5	63.9%
Medium	15.5	3.8	19.3	5.1	24.4	32.9%
Light	0.6	0.1	0.7	0.0	0.7	1.0%
Bus	1.2	0.5	1.6	0.0	1.6	2.2%
Total	39.1	21.3	60.4	13.9	74.4	100.0%
Percent	52.6%	28.7%	81.2%	18.8%	100.0%	

(Continued)

TABLE 2-5. (Continued)

## CONTRIBUTIONS TO STATEWIDE EXCESS EMISSIONS: 2000

	<u>California Registered</u>			<u>Out-Of-</u>		
	<u>Calif.</u>	<u>Federal</u>	<u>Total</u>	<u>State</u>	<u>Total</u>	<u>Percent</u>
	<u>Engine</u>	<u>Engine</u>		<u>Vehicles</u>		
<u>Oxides of Nitrogen (TPD)</u>						
Heavy	16.2	19.2	35.3	12.5	47.9	72.8%
Medium	10.0	2.6	12.5	3.3	15.8	24.0%
Light	1.3	0.2	1.4	0.0	1.5	2.3%
Bus	0.4	0.2	0.6	0.0	0.6	0.9%
Total	27.8	22.1	50.0	15.8	65.8	100.0%
Percent	42.3%	33.6%	75.9%	24.1%	100.0%	
<u>Unburned Hydrocarbons (TPD)</u>						
Heavy	8.0	6.8	14.8	2.9	17.7	49.3%
Medium	9.7	2.6	12.2	3.1	15.4	42.8%
Light	1.5	0.2	1.7	0.1	1.8	4.9%
Bus	0.7	0.3	1.0	0.0	1.0	2.9%
Total	19.9	9.9	29.8	6.1	35.9	100.0%
Percent	55.4%	27.7%	83.0%	17.0%	100.0%	
<u>Particulate Matter (TPD)</u>						
Heavy	12.0	10.8	22.8	5.0	27.9	63.0%
Medium	8.9	2.3	11.2	2.9	14.1	32.0%
Light	1.3	0.2	1.5	0.0	1.5	3.5%
Bus	0.5	0.2	0.7	0.0	0.7	1.5%
Total	22.7	13.5	36.3	8.0	44.2	100.0%
Percent	51.4%	30.5%	82.0%	18.0%	100.0%	

### 3.0 DEVELOPMENT AND VALIDATION OF I/M TEST PROCEDURES

Our objective in Tasks Two and Four of the project was to develop and validate two inspection test procedures for heavy-duty diesel vehicles: a Periodic Inspection and Maintenance Test (PIMT) procedure and a Roadside Smoke Opacity Check (ROC). The purpose of each of these procedures is to identify heavy-duty diesel vehicles which are producing excessive pollutant emissions. The ROC is intended to be used for random enforcement testing. For this reason, it was required that it be performable within the physical confines of a California Highway Patrol weigh station. The PIMT, as its name implies, is intended to be used in a periodic (e.g. annual or biennial) inspection program, analogous to California's existing Smog Check Program for light-duty vehicles. The results of these efforts are described in detail in Volume III, and are briefly summarized below.

#### 3.1 Test Procedures

Many candidate test procedures were considered. Most of these procedures appeared to be suitable for detecting one or more types of emissions-related defects, but no single procedure appeared capable of detecting all common defects in diesel engines. As a result, the test procedures proposed for validation testing included a number of candidate procedures--more than were considered desirable for the final product. The results of the validation testing were used to identify those specific tests among those proposed which were most effective in identifying high-emitting vehicles.

##### Roadside Smoke Opacity Check

Candidate procedures for the roadside smoke opacity check were limited to those which can reasonably be performed at a truck weigh station or other roadside environment, and were thus limited to off-dynamometer, non-invasive procedures. Four candidate procedures were proposed: a quick acceleration in gear; lug-down in gear (manual transmission vehicles only); stall

idle (automatic transmission vehicles only); and snap idle. The acceleration test procedure for the ROC consists of a full-power (accelerator to the floor) acceleration to governor speed in a suitably low gear. Two opacity values are recorded: the transient peak opacity, and the stabilized value after reaching governor speed. This procedure can be performed on either manual or automatic-transmission trucks.

The snap idle procedure consists of flooring the accelerator with the engine idling in neutral, causing it to accelerate to governor speed. Since there is no load on the engine except its own friction and inertia, this occurs very rapidly. Again, both the peak and the stabilized opacity are recorded.

The stall idle procedure is applicable only to vehicles with hydraulic torque converters. It is identical to the snap idle, except that it is performed with the gear selector of the automatic transmission set to "Drive" rather than neutral, and with the brakes set to prevent the vehicle from accelerating. The stalled torque converter absorbs considerable engine power, putting a significant load on the engine. Operation in this mode for more than a few seconds will overheat and damage the transmission, so caution is required.

The final test procedure proposed was a lug down using the vehicle's service brake. This test applies only to vehicles without hydraulic torque converters. In it, the driver holds the accelerator down with one foot, while pushing on the brakes with the other in order to load the engine. Since full engine power is absorbed in the brakes, this test must not be prolonged beyond a few seconds. Even so, it places great stress on the brakes, driveline, and transmission.

Smoke opacity in any of these tests could be judged either with an opacimeter on the stack or by a trained observer. For mass testing, the most

efficient approach would be to make a "first cut" by visual observation, with subsequent opacimeter testing for confirmation in marginal or disputed cases.

#### Periodic Inspection Procedure

The candidate inspection procedures proposed for the periodic I/M test are listed in Table 3-1. These procedures were intended to be performed in a diesel repair shop or similar facility. The proposed PIMT consists of visual and functional checks of emissions control equipment, together with smoke opacity measurements under acceleration, lugdown, and road-load conditions. HC and NO<sub>x</sub> concentration measurements in specific modes were also included in the candidate procedures, in order to evaluate their usefulness.

In developing these tests, we had to decide whether or not to base them on a chassis dynamometer or some other loading technique. Chassis dynamometers capable of loading a heavy-duty truck in steady-state operation typically cost \$100,000 to \$200,000 installed, and not all truck repair stations have them. Heavy-duty truck dynamometers with transient capabilities are even more expensive, and are found only in a few research organizations. A decision to rely on dynamometer tests would exclude many diesel repair shops from performing I/M tests. On the other hand, the need to test for excessive smoke emissions under load, and the greater controllability and repeatability of dynamometer loading compared to alternative means argued for a dynamometer-based procedure.

Contacts with dynamometer manufacturers revealed that enough chassis dynamometers were already in use in California to handle the anticipated test load. Obviously, many of these facilities are presently used for other activities and thus would not be available full time for I/M testing, but this large number of facilities now in use suggested that any others that might be needed could be built fairly readily. Thus, it was decided to develop test procedures based on the use of a chassis dynamometer.

In addition to a chassis dynamometer, we assumed that something analogous to the automatic Test Analyzer Systems (TAS) used in light-duty I/M

TABLE 3-1. PROPOSED PERIODIC I/M TEST PROCEDURES

---

---

VISUAL/FUNCTIONAL INSPECTION

Air filter "pop-out" indicator  
for excessive restriction  
Air supply and exhaust system for  
restrictions and leaks  
EGR valve (if fitted)  
Fuel injection pump adjustment seals  
Fuel supply system, pump, lines, and  
injectors for leaks  
Electronic control trouble lights  
Electronic control system computer,  
sensors, and actuators  
Trap-oxidizer system (if fitted)  
Oxidation catalyst (if fitted)

DYNAMOMETER TEST PROCEDURES

Full-power acceleration  
Lug-down--maximum torque at  
100% rated speed  
90% rated speed  
80% rated speed  
70% rated speed  
60% rated speed/max torque speed  
Road-load--75% torque at  
100% rated speed  
90% rated speed  
80% rated speed  
70% rated speed  
60% rated speed/max torque speed  
NO<sub>x</sub> concentration  
HC concentration

---

---

programs would be available for an I/M program. In addition to logic and recording capabilities, this system was assumed to be capable of measuring exhaust smoke opacity, and (optionally) HC and NO<sub>x</sub> concentrations. Preliminary inquiries with several instrumentation suppliers indicated that such a system would be well within the present state of the art, and that it could probably be sold at a price comparable to the more expensive of the TAS analyzers now used in California's Smog Check Program for light-duty vehicles. Detailed specification or development of such a system was not attempted in this project, however.

### 3.2 Validation Testing

Validation testing of the Roadside Opacity Check (ROC) and Periodic I/M Test (PIMT) procedures was accomplished in two stages. In the first stage, Radian and ARB staff applied the proposed ROC to 52 heavy-duty diesel trucks belonging to various government agencies, one private utility, and a commercial used-truck dealership. Based on the screening results, eleven of these trucks were brought into ARB's Haagen-Smit laboratory for additional testing, including both the PIMT procedure and gaseous and particulate emissions measurements.

#### Roadside Opacity Testing

Test results--Figure 3-1 displays the peak opacity results from the screening tests using the ROC acceleration procedure. The measured opacity level for each truck is plotted, together with the failure criterion used for each test. The trucks selected for dynamometer testing are indicated by the arrows underneath the figures. The acceleration procedure was found to be the most useful of the four ROC procedures for identifying high emitters. As the figures indicates, the failure rate for our test sample on this procedure was about 25 percent. The failure rates for the other procedures were quite variable--ranging from 14 percent for the stall idle peak to nearly 50 percent for the lugdown test. The latter value is probably unrepresentative, due to

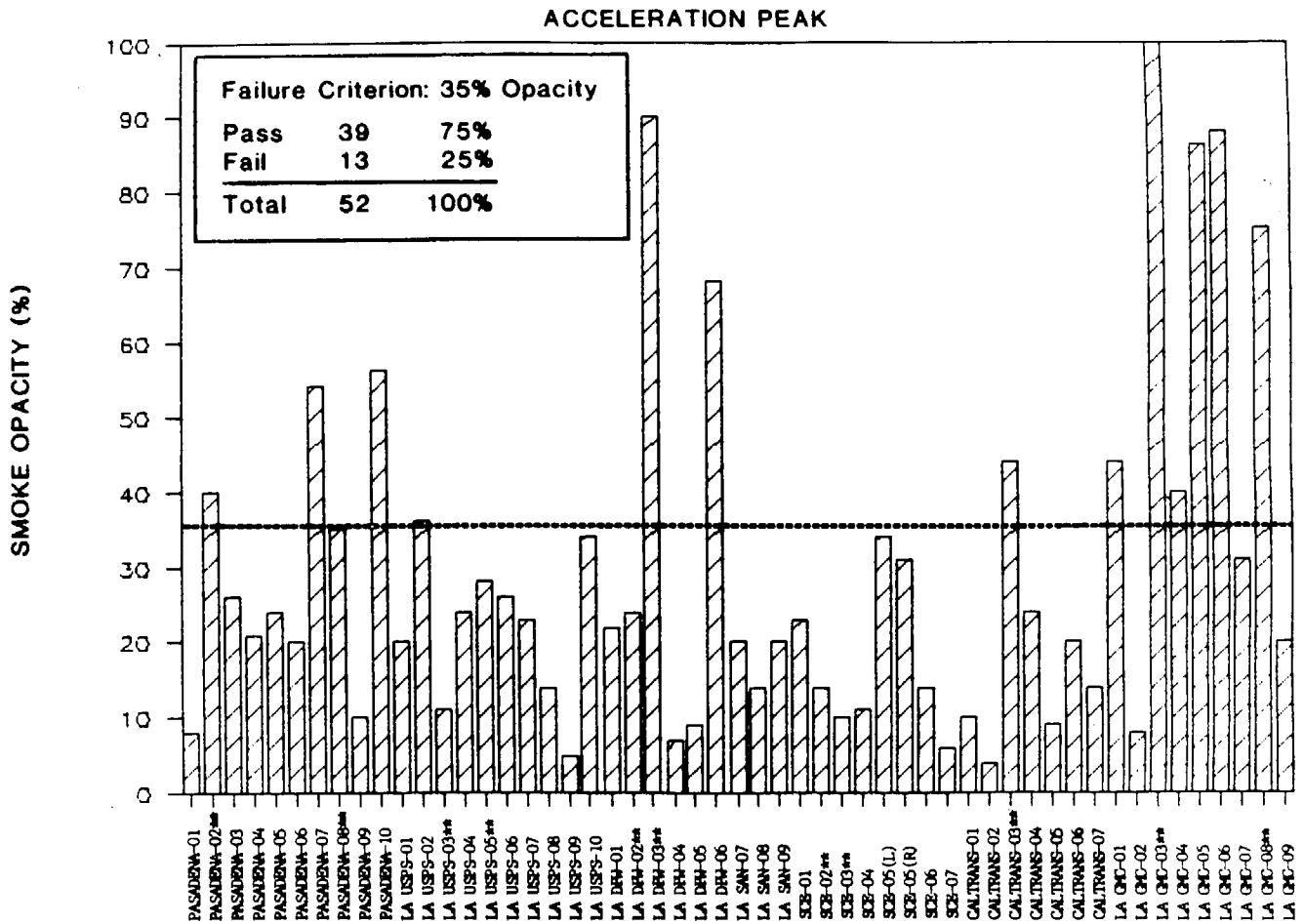


Figure 3-1. Bar Chart of Peak Acceleration Smoke Opacities from the Field Screening

the significant problems encountered in performing this test, and the fact that many of the high opacities measured were not confirmed in subsequent dynamometer testing.

Testing problems--Aside from the usual problems of field measurement on vehicles, no significant problems or concerns were experienced in conducting the stall idle or snap idle tests. These two tests could be conducted with the vehicle standing still. With the full-power acceleration test, it was necessary to have sufficient room to accelerate--and to slow down afterwards--without undue risk. Although no incidents were experienced in our screening tests, safety and the provision of an appropriate test area would be a concern in any widespread application of this procedure.

The acceleration/lug-down test used with manual-transmission vehicles required even more space than the acceleration alone, since the engine must run at near rated speed for several seconds during the lug-down. The effects of this operation on safety (especially in a congested area such as a truck depot) would be a significant concern. Shortage of space often resulted in the drivers having to apply the brakes too quickly to give a smooth reduction in engine speed. This led to "overshooting" the target of 60 percent of rated speed, and often caused stumbling and considerable excess black smoke as the engine was lugged down below its peak torque point, resulting in poor repeatability. This test also places considerable strain on the engine, brakes, and transmission, and could cause the drive tires to spin in some high-powered trucks.

#### PIMT and dynamometer emissions testing

On the basis of the screening tests described above, eleven trucks were selected for more extensive testing at ARB's Haagen-Smit Laboratory. The screening test results for these trucks are indicated by the asterisks in Figure 3-1. These trucks were delivered to the laboratory one at a time to be tested using the smoke opacity tests from the Periodic I/M Test (PIMT)

procedure, and a modified chassis-dynamometer version of the Federal 13-mode emissions test procedure. The latter test included measurements of HC, CO, NO<sub>x</sub>, and particulate emissions, fuel economy, and road horsepower (power delivered to the dynamometer rolls). Concentrations of HC, CO, CO<sub>2</sub>, and NO<sub>x</sub> in the raw exhaust were also measured and recorded.

The emissions testing at Haagen-Smit Laboratory used a chassis version of the old Federal 13-mode test, which is a steady-state test procedure. Since transient effects on HC and PM emissions are important, the current Federal test procedure involves operation over a transient test cycle. The heavy-duty dynamometer at the Laboratory was incapable of generating reproducible transient conditions, however, so that transient emissions testing could not be performed in this study. This undoubtedly affected the results. ARB and the Southern California Rapid Transit District are currently cooperating on the development of a heavy-duty chassis dynamometer with transient emissions testing capability, and it is recommended that this or a similar facility be used in any further studies in this area.

Based on the results of these tests, six of the higher-emitting trucks in the sample were sent out for diagnosis and repair of emissions-related malfunctions. These trucks were then returned to the laboratory for another round of testing.

#### Analysis of Test Results

The statistical analysis of the data generated by the validation testing program addressed four main issues.

- How do visual smoke opacity estimates compare to opacity values measured with an opacimeter?
- How well do smoke opacity values correlate with particulate emissions?

- Which smoke opacity tests are most effective in identifying high particulate and HC emitters, and how effective are they?
- How well can composite  $\text{NO}_x$  and HC emissions over the entire test cycle be predicted from concentration data for individual modes? Are these relationships strong enough to identify excess emitters reliably?

Visual vs. Measured Smoke Opacity--Figures 3-2 and 3-3 contain cross plots comparing the smoke opacity measured with the opacimeter with the visual opacity estimate for two test modes: acceleration peak and snap idle peak. Each of the visual and opacimeter values plotted is the average of two test for two test runs. For each figure, the opacimeter measurement is plotted on the horizontal axis, and the visual estimate on the vertical axis. Cross-hairs indicating the failure criterion for that mode are also shown on each plot. As these figures indicate, the correlation between the estimated and measured value is fairly strong, and the RMS error in the estimates was of the order of 10 percent opacity for both.

These data indicate a fair degree of correspondence between the visual opacity estimates and the opacimeter data in the moderate-to-high opacity range. This range is the one of greatest interest for smoke observation. It was much harder to estimate smoke opacities accurately in the lower opacity range, and a greater number of significant errors occurred. Relatively few of these errors would have changed the outcome of an I/M test, however, as the small populations in the upper left and lower right quadrants of the plots indicate. These data indicate that a visual screening approach could be feasible with the ROC, which would greatly simplify its implementation in the field. An officer could distinguish passing from failing levels by eye in most cases. Marginal or protested cases could then be confirmed using an opacimeter.

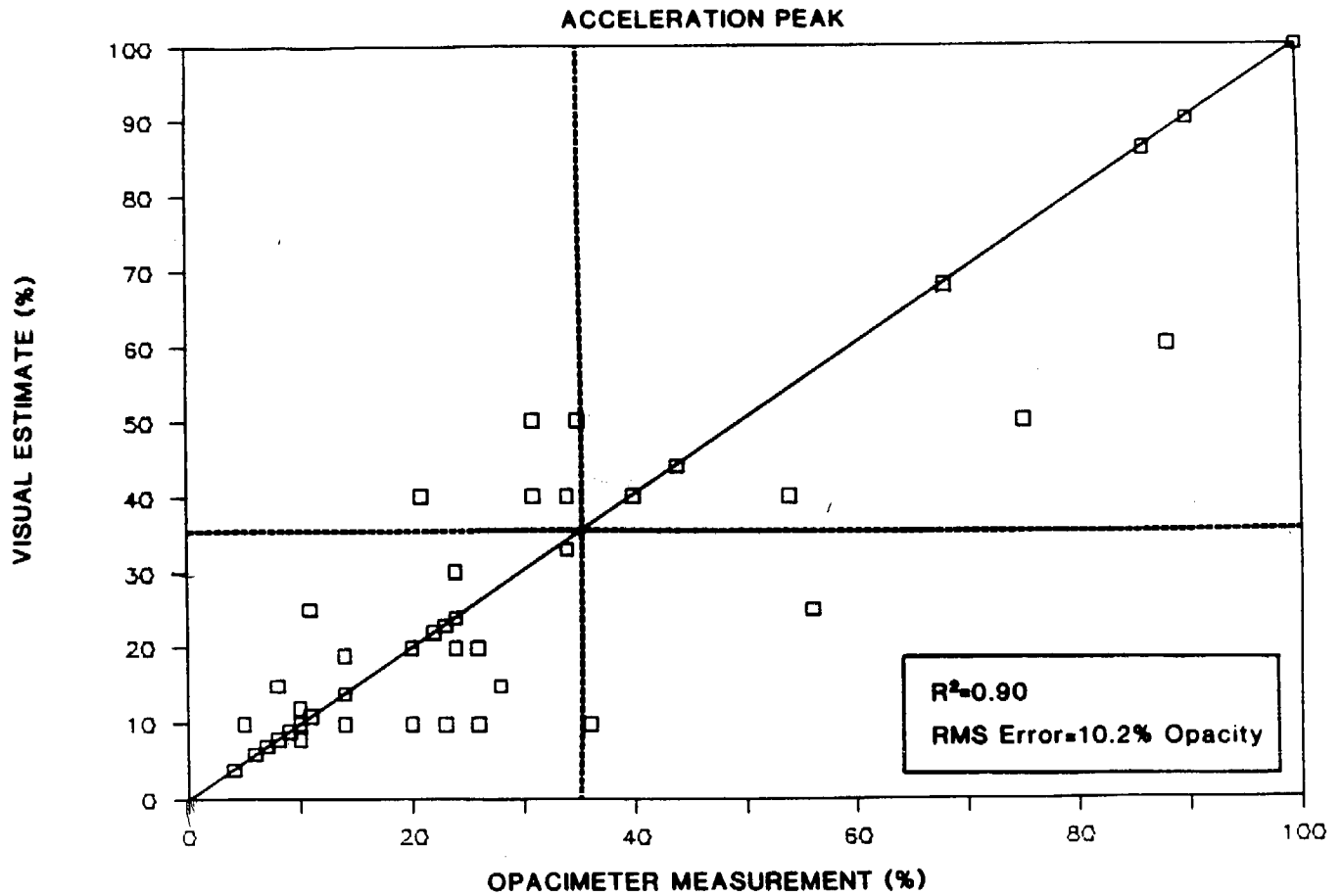


Figure 3-2. Visual vs. Measured Smoke Opacity (Acceleration Peak)

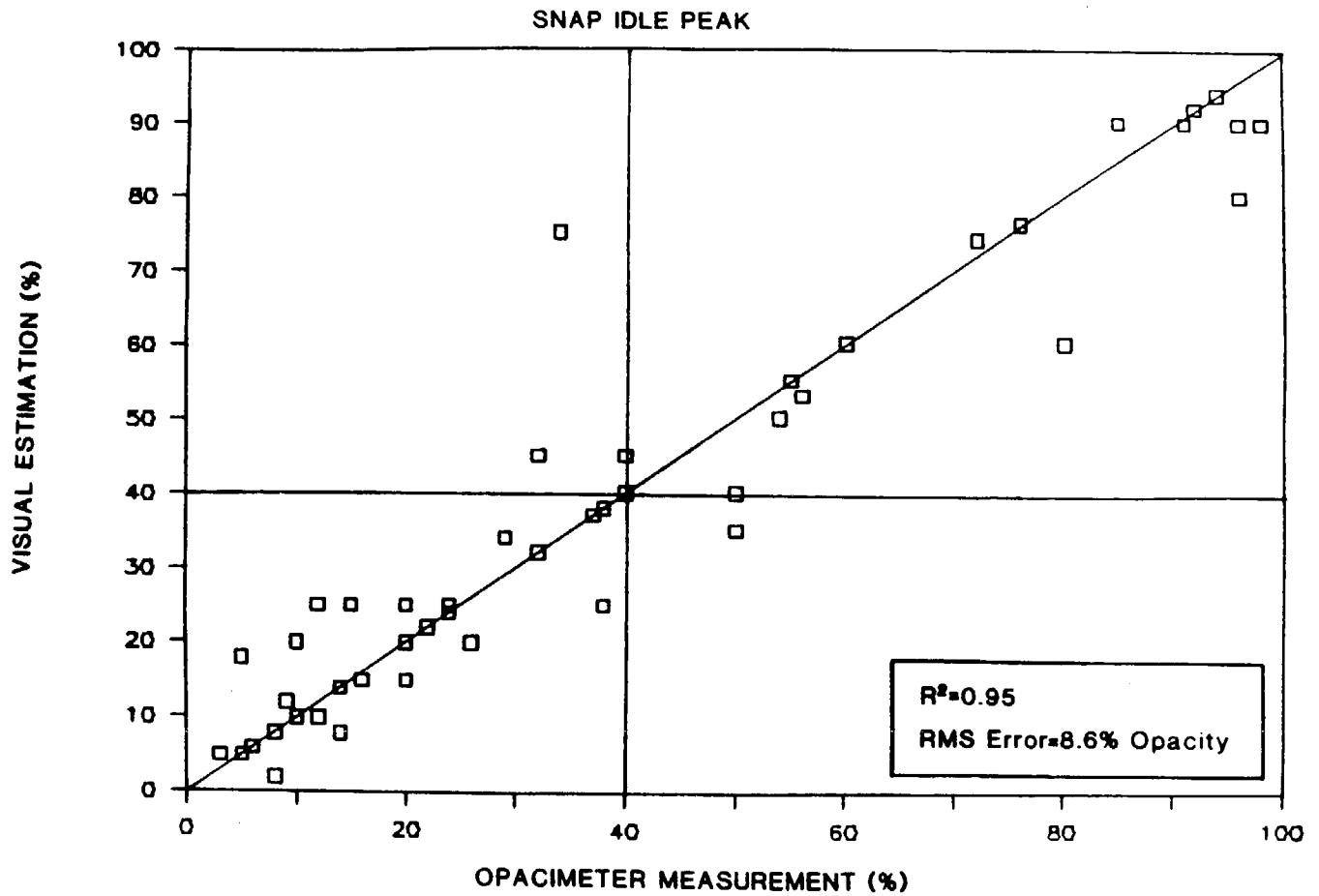


Figure 3-3. Measured vs. Visual Smoke Opacity  
(Snap Idle Peak Reading)

Correlation of Smoke Opacity With Particulate Emissions--Correlation and multiple linear regression analyses were performed, comparing the smoke opacity data from the PIMT with cycle-composite particulate emissions from the chassis 13-mode cycle. Perfect correlation was not anticipated, as it was known that some problems (e.g. misset smoke limiters) can lead to very high peak smoke opacities, while having only a moderate effect on cycle-composite emissions (indeed, the acceleration smoke limiter should have had no effect on PM emissions in these steady-state tests).

Correlation analyses indicated that the best predictors of 13-mode PM emissions were the smoke opacity at the maximum torque point (lug-down smoke), 75 percent power at rated speed (road load smoke), and 100 percent power at rated speed (maximum power smoke). Surprisingly (given the steady-state test cycle) acceleration peak smoke also turned out to correlate reasonably well with PM emissions. Subsequently, regression analyses were carried out using lug-down, road-load, and acceleration peak smoke opacities. The results for the lug-down and acceleration peak regressions are plotted in Figures 3-4 and 3-5.

The best one-variable model for PM emissions was the one having lug-down smoke opacity ( $O_{ld}$ ) as the independent variable.  $R^2$  for this model was calculated as 0.60, indicating only fair correlation. The results of this model are plotted as the dashed line in Figure 3-4.

Examination of Figure 3-4 shows that the visual fit of the data could be substantially improved if the two points marked PASADENA-02 were excluded. These points represent before and after-repairs measurements on one truck. This truck had the only automatic transmission in the group, and was later found to be suffering from overheating, due to the installation of an incorrect cylinder head gasket. Either or both of these could have affected the correlation between smoke and PM emissions. However, repeating the regression without these two data points did not improve the statistical fit. The results of this calculation are plotted as the solid line in the figure.

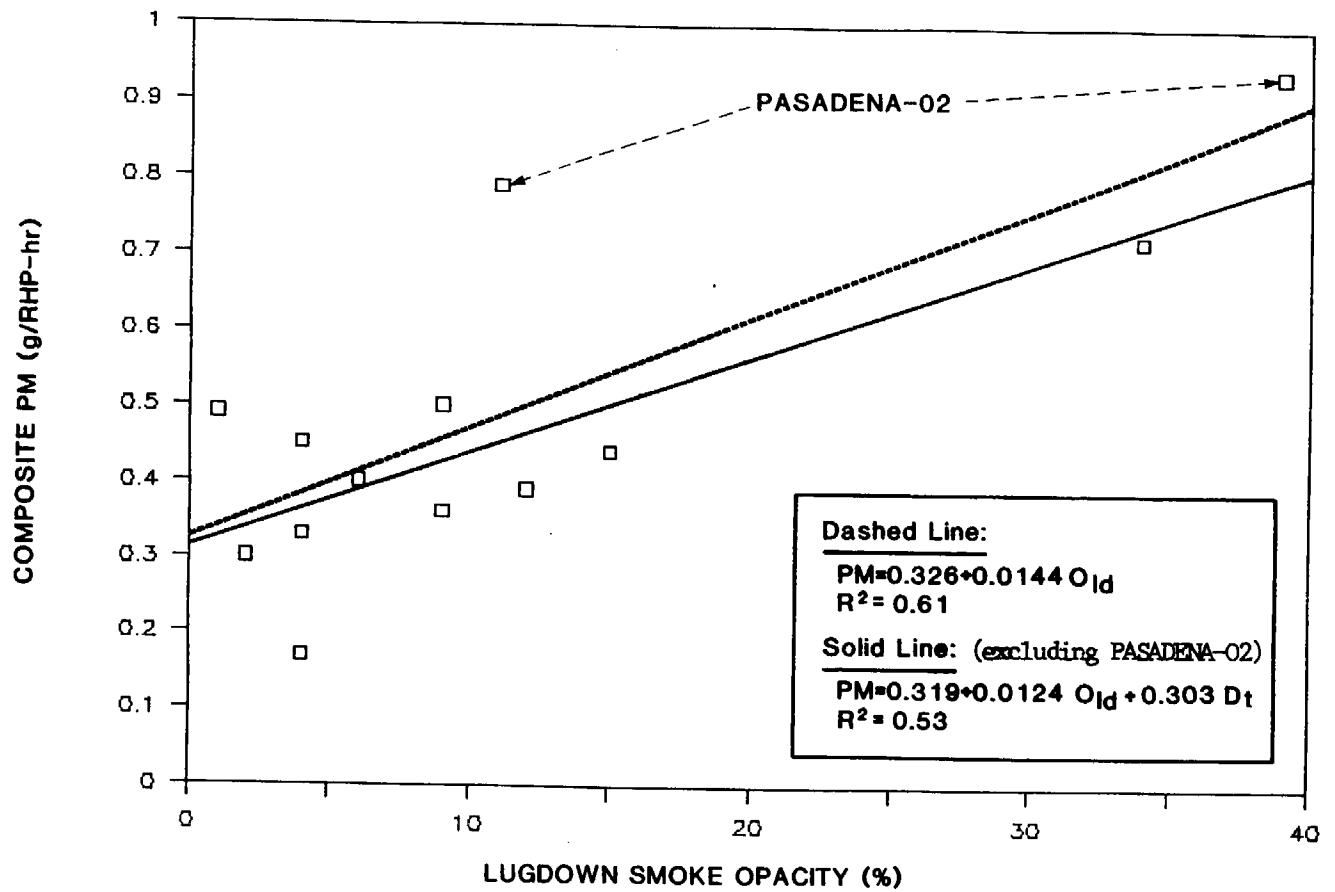


Figure 3-4. Particulate Emissions vs. Lug-Down Opacity

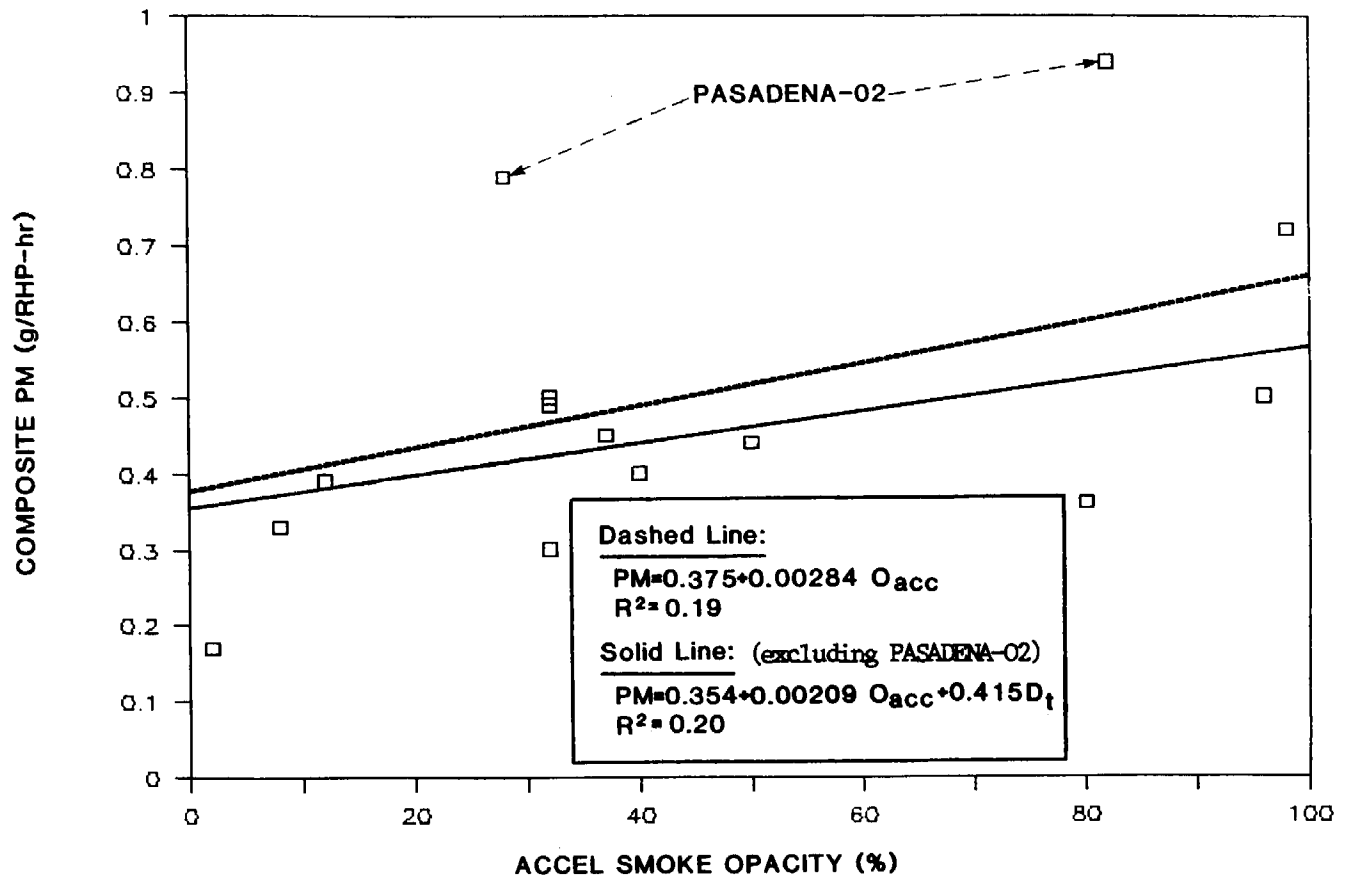


Figure 3-5. Particulate Emissions vs. Acceleration Peak Smoke Opacity

Part of the reason for the poor fit is undoubtedly the limited range of PM emissions data in the remaining sample.

Figure 3-5 is a plot of acceleration peak smoke opacity ( $O_{acc}$ ) vs. particulate emissions. As this figure shows, the correlation is rather poor--the best fit model has an  $R^2$  value of only 0.19. This model is plotted as the dashed line in Figure 3-5. Again, the exclusion of data for truck PASADENA-02 had little effect on the quality of the fit (plotted as the solid line in the figure). This poor correlation is not surprising, since several of the trucks exhibiting high transient smoke emissions during acceleration had rather low steady-state emissions, and these are what would have been measured in the steady-state emissions tests performed.

Effectiveness in Identifying Excess Emitters--Table 3-2 shows the results of a pass/fail analysis of the 14 data points from the validation testing for which both particulate and smoke measurements were available. This table shows the number of "true positive", "false positive", "true negative" and "false negative" results generated by each test mode. A "true positive" is a high-emitting vehicle which fails the smoke opacity test; a "false positive" is a low-emitting vehicle which fails. Similarly, a "true negative" is a low-emitting vehicle which passes the test; and a "false negative" is a high-emitting vehicle which passes. False positives and false negatives correspond to errors of commission and errors of omission, respectively. For this analysis, "high-emitting" vehicles were defined as those having either PM or HC emissions in excess of 0.6 g/RHP-hr in the 13-mode emissions test.

Table 3-2 also shows the percentage of the total excess HC and PM emissions identified by each of the tests. Consistent with the definition of a "high emitter", "excess" emissions were defined as those exceeding 0.6 g/RHP-hr for either HC or PM. As the table shows, several of the smoke opacity tests were equally effective in identifying high particulate emissions, but the acceleration peak and snap idle peak were the most effective in

TABLE 3-2. EFFECTIVENESS OF SMOKE OPACITY TESTS IN IDENTIFYING  
 HIGH EMITTERS

Test	Outpoint (Opacity)	True Neg	False* Neg	False** Pos	True Pos	Total	Percentage of Excess Emissions Detected	
							PM	HC
Accel Peak	35%	4	3	2	5	14	71%	67%
Accel Stabilized	6%	6	7	0	1	14	18%	29%
Snap Idle Peak	35%	3	4	3	4	14	71%	58%
Snap Idle Stabilized	10%	6	6	0	2	14	71%	39%
Lug-Down	20%	6	6	0	2	14	71%	39%
Road Load	5%	6	8	0	0	14	0%	0%

\* Error of omission

\*\* Error of commission

identifying high HC emissions. The acceleration peak test also had the fewest false negatives of any of the tests. In addition, two false positives (errors of commission) with the acceleration test should not really be considered as such. Each of the trucks in question exhibited transient smoke levels high enough to be offensive, and would likely have exhibited higher-than-normal transient particulate emissions, even though its steady-state particulate emissions were low.

Modal NO<sub>x</sub> and HC Concentrations vs. Emissions--In developing our recommended test procedures, we speculated that measurement of exhaust gas NO<sub>x</sub> and HC concentrations in specific operating modes might be useable for identifying vehicles emitting excessive amounts of these pollutants. This approach is used in nearly all I/M programs for spark-ignition vehicles. In order to evaluate the effectiveness of this type of test for heavy-duty diesel vehicles, we performed a linear regression analysis to compare the modal emissions concentrations to the cycle composite values. The results of this analysis showed that the NO<sub>x</sub> concentration in mode 4, alone, gave the best correlation with the cycle composite NO<sub>x</sub>. This relationship is shown in Figure 3-6. For HC emissions, the linear regression analysis indicated that a combination of HC concentrations in modes 6 and 14 gave the best prediction of cycle-composite HC emissions. A cross plot of actual HC emissions vs. emissions predicted by this model is given in Figure 3-7.

### 3.3 Analysis of the NYCDEP Database

The validation test results showed a statistically significant relationship between smoke opacity measurements and particulate emissions measured under steady-state conditions. A larger database was considered desirable, however, in order to increase our confidence in the statistical validity of the procedures. In addition, it was considered very desirable to assess the correlation between smoke opacity and transient HC and particulate emissions, since actual vehicle operation is characterized by mostly transient conditions.

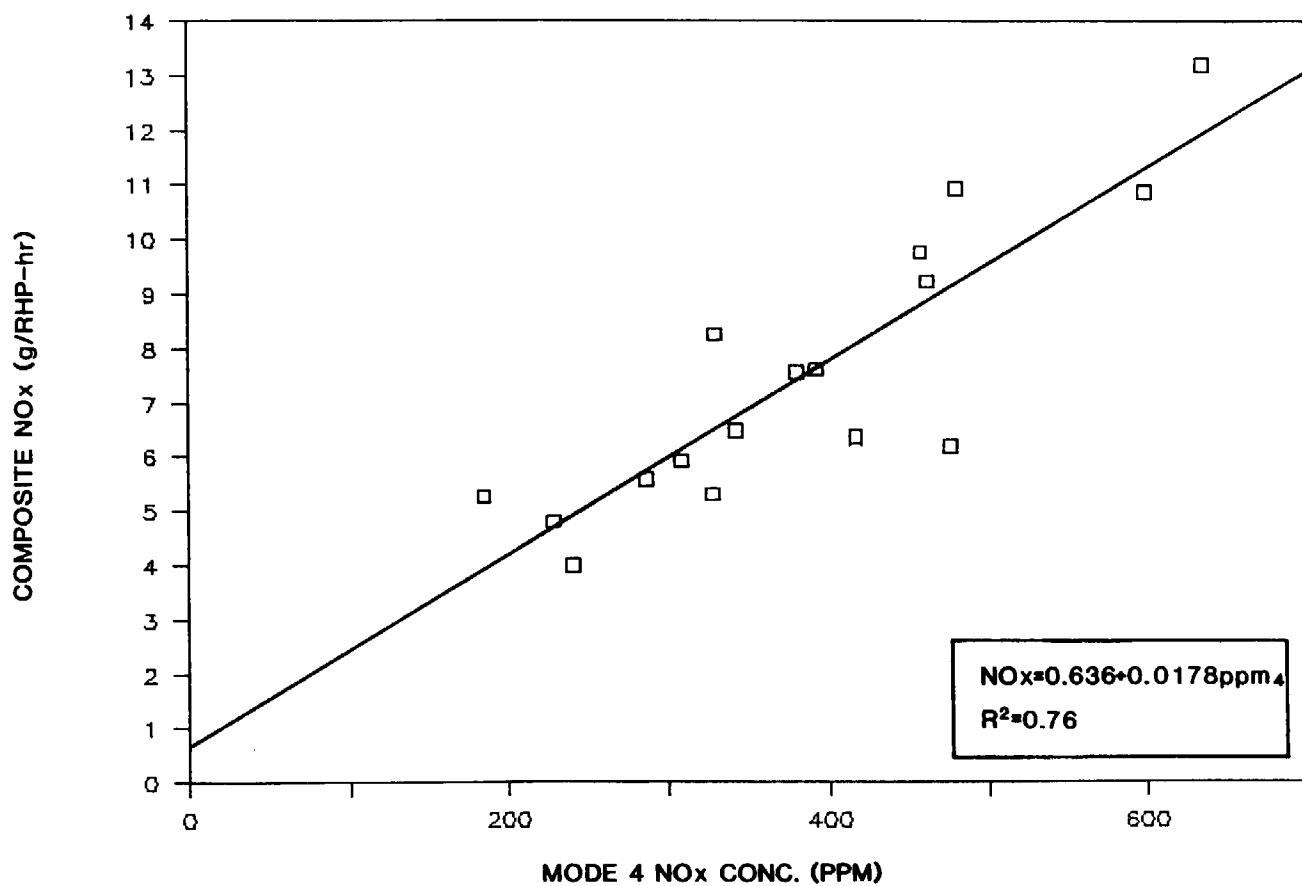


Figure 3-6. NO<sub>x</sub> Emissions vs. Mode 4 Concentrations

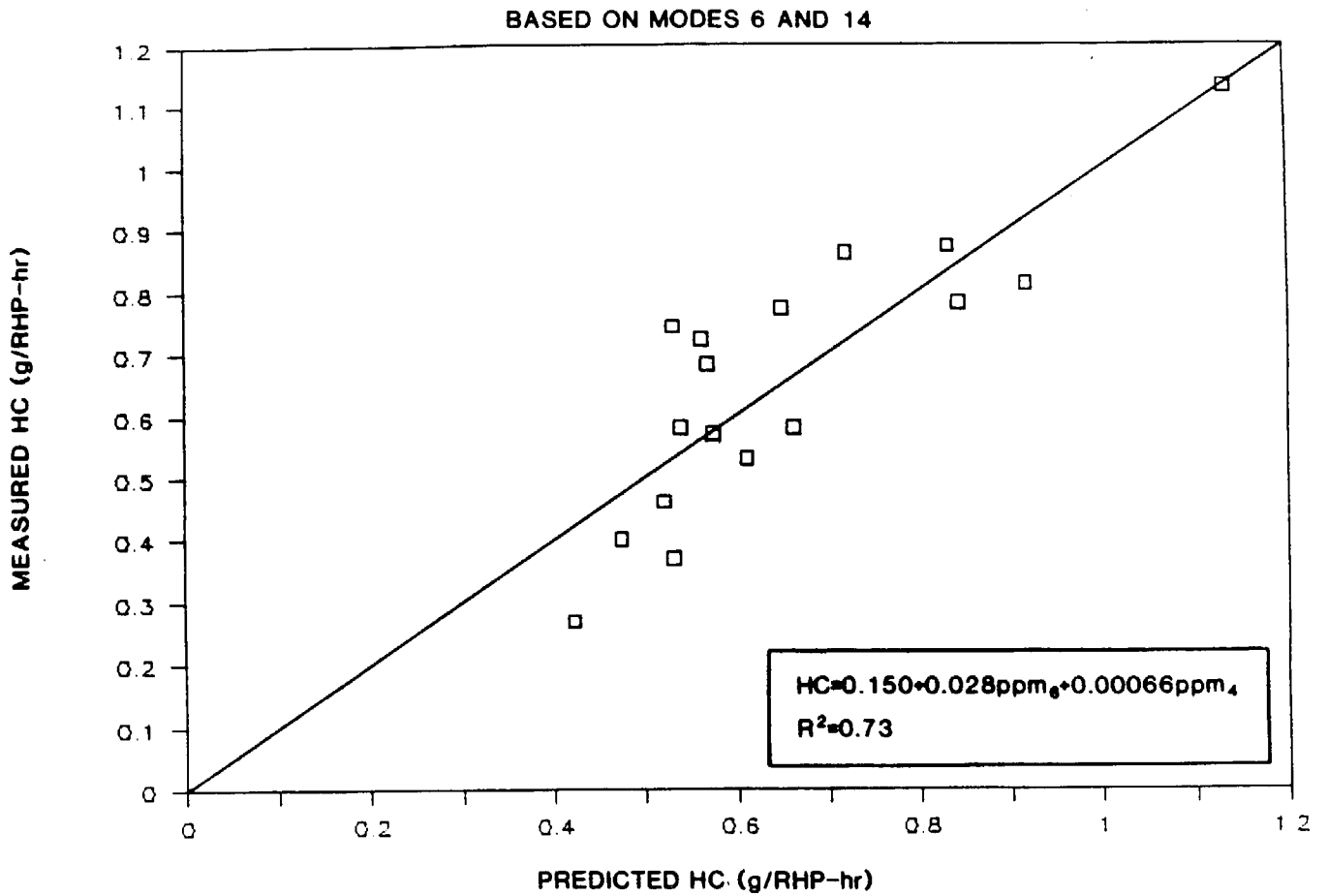


Figure 3-7. Predicted vs. Actual HC (Based on Modes 6 & 14)

A suitable database was made available by the Frost Street emissions laboratory of the New York City Department of Environmental Protection (NYCDEP). This database consists of more than 315 emissions tests on 133 diesel buses, and another 118 tests on 20 heavy-duty diesel trucks. To our knowledge, this is by far the largest collection of in-use diesel emissions data ever collected.

Our statistical analysis of the NYCDEP database followed the same pattern as the validation test analysis. Single and multiple linear regression were used to establish the relationship between smoke and particulate emissions. The results of these regressions are shown in Figures 3-8 through 3-10, showing the relationship between smoke opacity and particulate emissions in three different emissions test cycles. A strong positive correlation between smoke opacity and particulate emissions is clearly visible in all three figures.

In addition to the linear regression analyses, a pass/fail analysis was performed using the same failure criteria as for the validation testing. The effects of two I/M tests were simulated: acceleration opacity and road-load cruise opacity. Buses were classed as passing or failing an I/M test based on their opacity measurements; and as low or high emitters based on their emissions on the NYB-2 cycle. Our analysis compared the numbers of high and low emitters which passed or failed the simulated I/M test, using two different levels of stringency. Table 3-3 shows the results of this analysis.

For the bus fleet tested, using the less stringent failure criteria, 69.3 percent of the buses were low emitters, and all of these passed the I/M test (there were no false positives). The remaining 30.7 percent of the buses were classed as high emitters. Of these, more than two-thirds (20.8 percent of the total) also passed the I/M test, causing them to be classed as false negatives. Only 9.9 percent of the buses failed the I/M test. However, this small group accounted for more than 68 percent of the total excess particulate emissions and 80 percent of excess hydrocarbon emissions for the entire fleet.

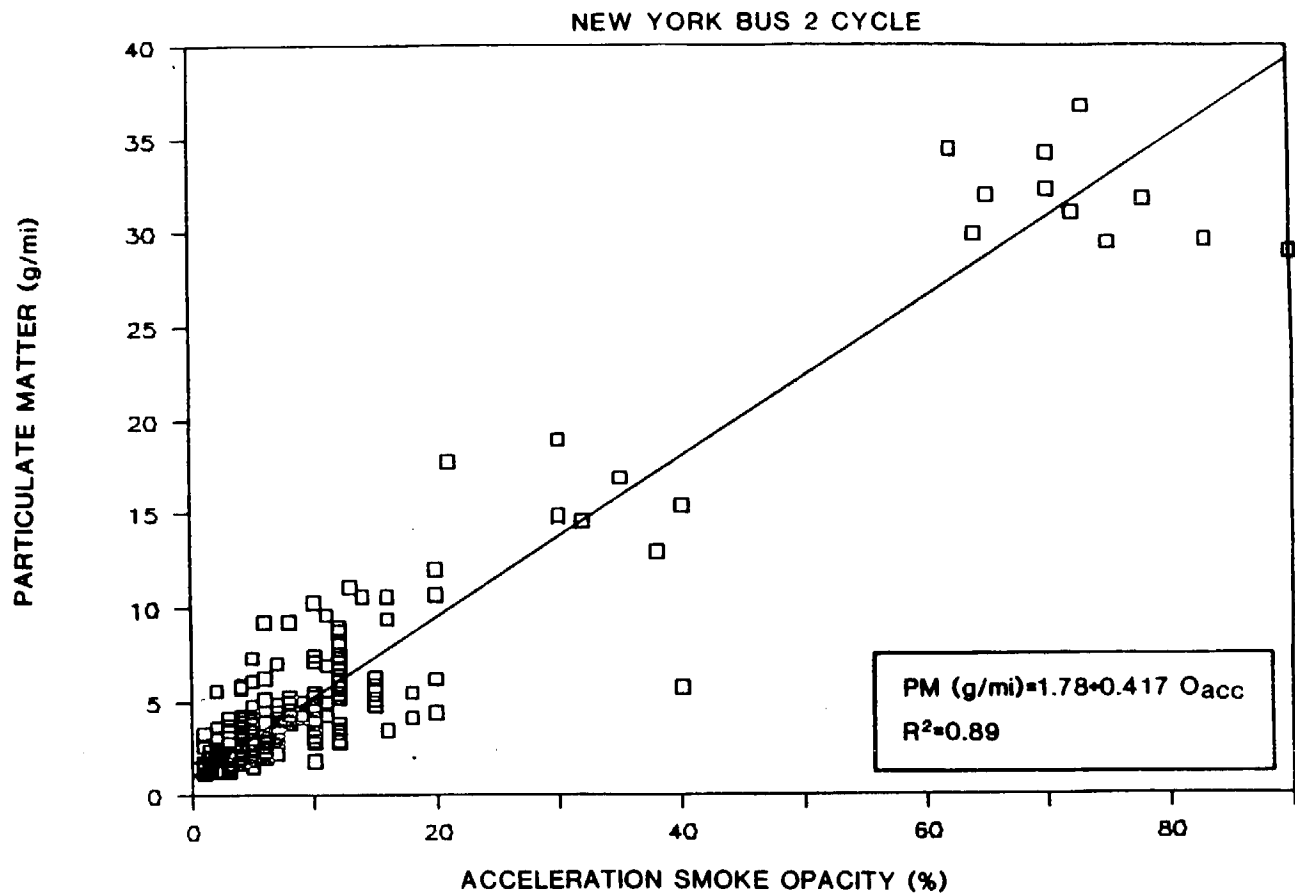


Figure 3-8. Acceleration Smoke Opacity vs. Particulate Emissions  
(New York Bus 2 Cycle)

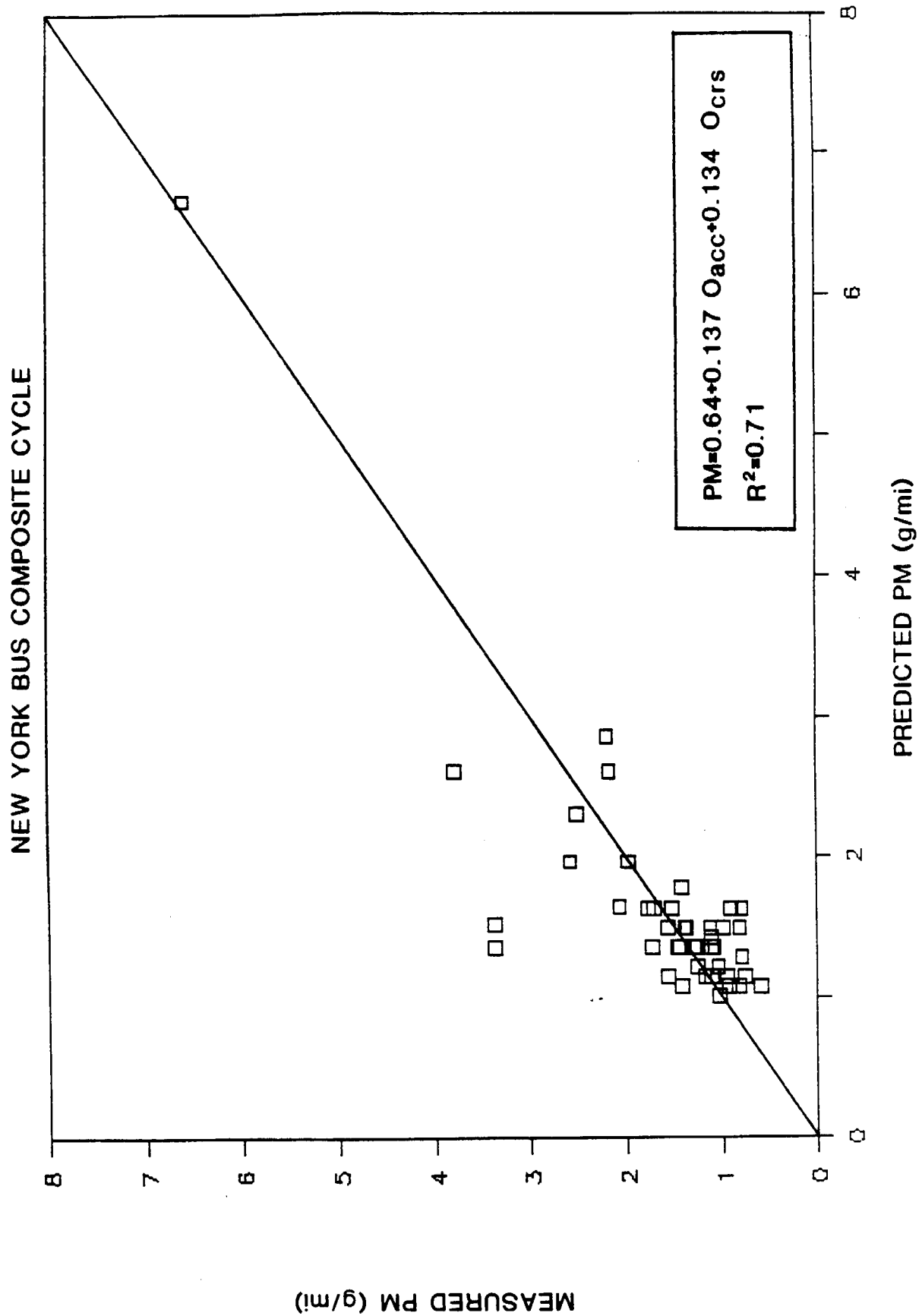


Figure 3-9. Actual particulate emissions vs. emissions predicted from acceleration and cruise mode opacities: New York Bus Composite Cycle.

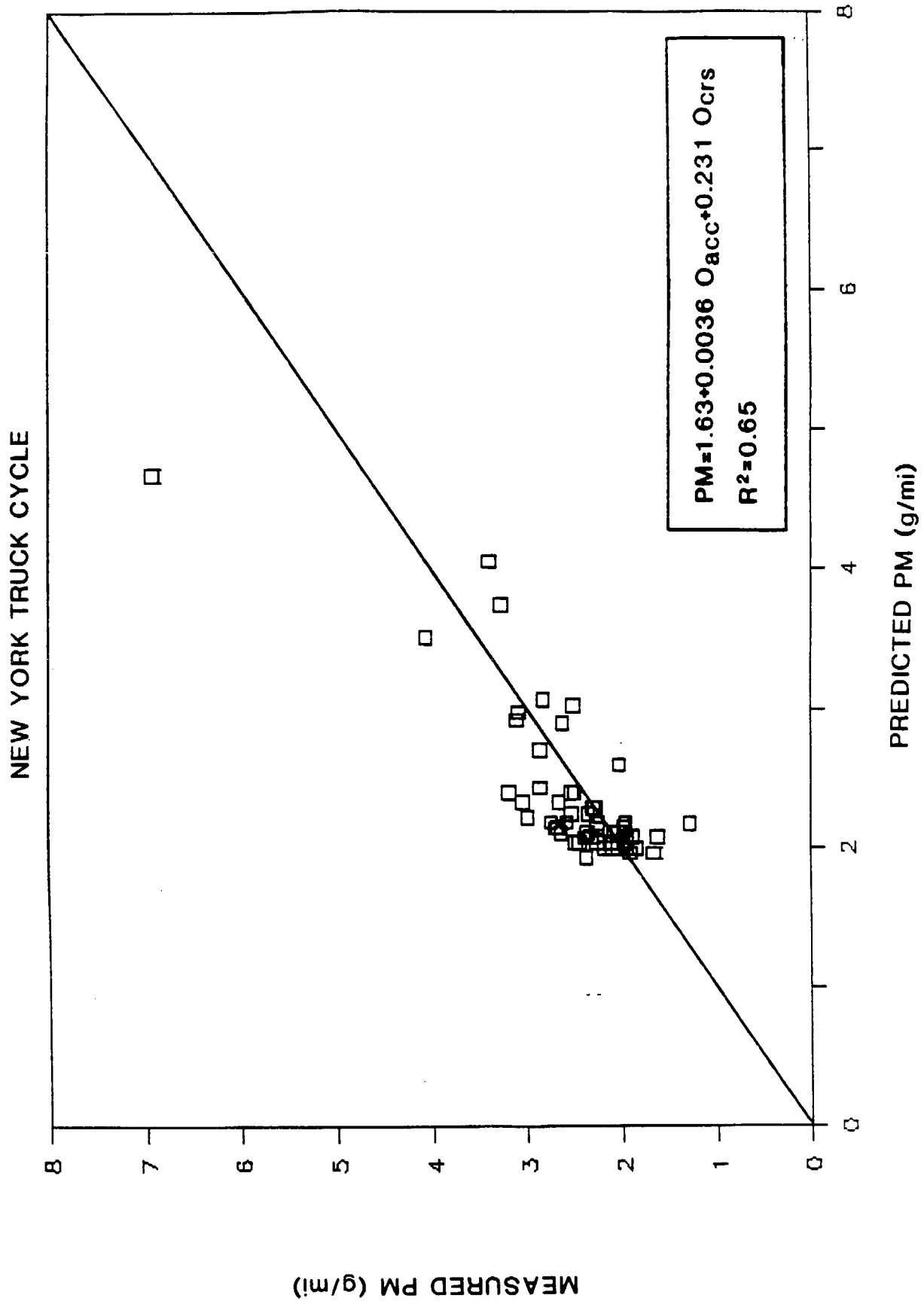


Figure 3-10. Actual particulate emissions vs. emissions predicted from acceleration and cruise mode opacities; New York Truck Cycle.

TABLE 3-3. PASS/FAIL ANALYSIS FOR TWO SETS OF I/M FAILURE  
 CRITERIA: NEW YORK BUS DATABASE

<u>Original Failure Criteria</u>				
$O_{acc} > 35\%$ or $O_{crs} > 6\%$				
	No. of Veh.	Percent of Veh.	Mean Emissions (NYC Bus 2)	
			PM	HC
True Negative	147	69.3	3.08	7.90
False Negative	44	20.8	8.21	10.98
False Positive	0	0.0	--	--
True Positive	<u>21</u>	<u>9.9</u>	<u>26.67</u>	<u>37.53</u>
Total	212	100.0		
Percent Excess Emissions Detected			68.5%	80.8%

<u>Revised Failure Criteria</u>				
$O_{acc} > 15\%$ or $O_{crs} > 3\%$				
	No. of Veh.	Percent of Veh.	Mean Emissions (NYC Bus 2)	
			PM	HC
True Negative	139	65.6	3.04	7.89
False Negative	34	16.0	7.17	10.71
False Positive	8	3.8	4.28	7.96
True Positive	<u>31</u>	<u>14.6</u>	<u>20.71</u>	<u>29.26</u>
Total	212	100.0		
Percent Excess Emissions Detected			80.9%	83.4%

Mean emissions from the failing group were 26.7 g/mi of particulate, which is nearly nine times the mean for the low-emitting group, and three times the mean for the false negative group. Thus, while these tests did not detect all high emitters, they did detect the highest emitters, which account for most of the excess emissions.

Examination of the bus data, as well as the results of work for ARB indicated that, for buses the failure criteria for smoke opacity could be made considerably more stringent than our initial proposals. Accordingly, the above analysis was redone using failure criteria of 15 percent opacity in acceleration mode and 3 percent opacity in cruise. This reduced the percentage of false negatives from 20.8 to 16 percent, increasing the number of true positives by the same amount. At the same time, however, eight false positive tests (low-emitting vehicles which failed the I/M test) were also created. All of these failed only in the acceleration mode--none failed the cruise mode test. The term "false positive" is thus somewhat of a misnomer, as each of these buses was emitting mildly offensive levels of visible smoke on acceleration, even though their overall particulate levels were not excessive by our definition.

### 3.4 Conclusions and Recommendations

Based on the test data and analysis presented here, the following conclusions and recommendations can be made.

#### Roadside Opacity Check

- The acceleration smoke opacity test appears to be the most effective of the four candidate procedures proposed for the ROC. However, a change in instrumentation to measure the "average" rather than the peak opacity might improve the correlation with emissions and should be investigated further. This test also has the advantage of being applicable to either

manual or automatic transmissions. The stall idle test involves very similar operating conditions and produces similar results. It appears to be an acceptable alternate test for vehicles with automatic transmissions.

- The proposed failure criterion for peak opacity in the acceleration and stall idle tests was 35 percent (or 5 percent over the Federal Peak certification, if that is higher). Based on our limited data, this appears to be appropriate for trucks, and we recommend that it be retained. Alternatively, an opacity cutoff of 50 percent (equivalent to the Federal Smoke Test criterion) could be used. This would result in a much lower failure rate, and some trucks with visually offensive smoke levels would pass. However, the higher cutoff should still suffice to identify gross emitters. Buses appear to be capable of meeting a more stringent failure criterion of 15 percent peak smoke opacity.
- Some trucks may exhibit high transient peak smoke opacity, even though their overall PM emissions are moderate. Thus, the acceleration test could be expected to generate a significant number of "errors of commission" if only PM emissions (and not visible smoke) were the issues of concern. However, all vehicles subject to such "errors of commission" would still be exhibiting visually offensive smoke. In a program concerned with both smoke and PM emissions, these could not be considered errors of commission.
- Separate failure criteria were proposed for stabilized smoke opacity in the acceleration and stall idle tests. Based on the New York City database, these modes can identify some additional high emitters, but they also create a disproportionate number of errors of commission. We recommend omitting these test criteria from the final procedure.

- The snap idle test procedure is easier and requires less space to perform than the acceleration test, but the results correlate poorly with emissions--resulting in a greater number of errors of commission. It appears that some engine designs are more sensitive than others to the unrealistic operating conditions involved. We recommend against general use of this test, although it may be useful for specific classes of vehicles such as buses.
- The lug-down test procedure using the vehicle's service brakes is difficult to perform, shows poor repeatability, and is less effective than other procedures in identifying high emitters. We recommend that this test be dropped.
- Visual estimates of smoke opacity--even when performed by persons without formal training in opacity estimation--were found to correlate well with the values measured with the opacimeter. Since no equipment or contact with the vehicle is required, visual estimation is much faster than opacimeter measurements. We recommend that this approach be used for initial screening in ROC, with doubtful or protested cases being resolved by retesting with an opacimeter. Using this approach, it would be possible to screen essentially every truck passing through a truck weigh station or similar facility.

#### Periodic I/M Test

- Peak smoke opacity during acceleration correlates fairly well with particulate emissions under transient operating conditions. The acceleration peak opacity is also a good measure of offensive in-use smoke. The acceleration test showed good repeatability, and was the most effective test for identifying

high hydrocarbon and particulate emitters, both in the Task Four tests and the NYCDEP data. We recommend that this test be included in the PIMT.

- The addition of smoke opacity in road-load cruise to the peak smoke opacity significantly improved the correlation between smoke measurements and particulate emissions in the NYCDEP databases. This test also identified some high-emitting vehicles in the NYCDEP data base which passed the acceleration test, and it generated no errors of commission. We recommend that this test be included in the PIMT as well.
- The failure criterion proposed for the dynamometer acceleration test in the PIMT was 35 percent peak opacity, or 5 percent over the Federal certification value if that is higher. This criterion appears to be appropriate. For the road load cruise test, the proposed failure criterion was 5 percent opacity. This appears slightly lax--a cutoff of 4 percent opacity at 75 percent power and rated speed appears more appropriate.
- Peak lug-down smoke opacity also correlates well with steady-state emissions, but we have no data to assess its correlation with transient results. This test identified fewer high emitters in the Task Four testing than did the acceleration test, and did not identify any high emitters that the acceleration test missed. In a larger sample, however, this might not have been true. This test is also clearly related to on-road smoke emissions in full-power operation. We recommend that this test be included in the PIMT.
- As discussed above for the ROC, the snap idle test correlates poorly with emissions, and generates more errors of commission than the acceleration test. This is apparently due to design

features which make some engines more sensitive to this test than others. We recommend that this test be dropped from consideration for general use, although it may still prove useful with specific makes of engines.

- $\text{NO}_x$  concentrations in modes 4 and 5 (50 percent and 75 percent power at rated speed) of the chassis dynamometer test correlate well with cycle composite  $\text{NO}_x$  emissions. This measurement could be used to identify vehicles with excessive  $\text{NO}_x$  emissions due to tampering or improper replacement of fuel injection pumps. We recommend that this measurement be included in the PIMT.
- The combination of HC emissions in modes 6 (full power/rated speed) and 14 (no load/governor speed) correlates well with cycle-composite HC emissions measured in the 13-mode cycle. Further research will be needed to determine whether this correlation will hold for HC emissions in transient operation, but we consider it likely that this will be the case. We recommend that this measurement also be included in the PIMT.

#### General

- The data and analysis presented here demonstrate the technical feasibility of identifying heavy-duty diesel vehicles which are excessive emitters, by means of simple tests based on smoke opacity and (possibly)  $\text{NO}_x$  and HC concentrations.
- Further work with a larger truck sample is needed to refine the failure criteria, to improve estimates of the failure rates and emissions reductions from repaired vehicles, and to better define the relationships between smoke opacity and in-use particulate and HC emissions. To reflect actual operating

conditions, this work should be conducted using a transient test cycle on a suitably-equipped chassis dynamometer. As a possible alternative, techniques for mass emission measurements on vehicles in normal use might be developed.

In this further testing, steps should be taken to obtain a random sample of trucks in use, rather than relying on volunteer fleets. The volunteer (primarily publicly-owned) fleets in our test program exhibited much lower smoke than observed in the visual smoke survey. This probably reflects significantly better maintenance than the average. A realistic assessment of in-use emissions must include the occasional "gross" emitter, which is unlikely to be found in a well-maintained fleet.

#### 4.0 COSTS, EMISSION REDUCTIONS, AND COST-EFFECTIVENESS OF ALTERNATIVE HEAVY-DUTY DIESEL I/M PROGRAMS

In Task Three of the project, Radian estimated the costs and emission reductions due to various alternative approaches to heavy-duty diesel I/M, and evaluated the cost-effectiveness of each. This task was the last one completed. The results of this Task are presented in Volume IV, and briefly summarized below.

##### 4.1 Procedure

After analysis of the results of Tasks One and Four, Radian defined a number of alternative I/M scenarios for further investigation. A simple model of I/M program effects on the frequency of occurrence of each type of emissions defect was developed, and used to prepare revised estimates of defect frequency for input to the heavy-duty diesel emissions model described in Volume II. The I/M effects model also calculated the average repair costs, probability of requiring repairs, and the probability of being fined for tampering for each vehicle class under each I/M scenario. These were used to estimate the costs of each type of program.

Design of an inspection and maintenance program for heavy-duty diesel vehicles presents many difficult issues. Because of the differences in technology, ownership, and operating patterns, existing I/M programs for light-duty vehicles may not be a good model for heavy-duty diesel I/M. Other existing enforcement programs aimed at heavy-duty trucks (such as CHP weigh stations and safety inspection programs) should be considered as models as well.

In order to effectively reduce emissions, while minimizing the burden on vehicle owners, the primary goals of a heavy-duty diesel I/M program should be the following:

- deter tampering with emission controls;
- detect tampering which is not deterred, and require that it be corrected;
- identify gross-emitting vehicles, and require that they be repaired; and
- encourage proper maintenance and awareness of the importance of emission controls in the bulk of the heavy-duty diesel fleet.

The I/M program scenarios investigated in this study were chosen with these goals in mind. They consist of a number of variations on two basic approaches: a dynamometer-based periodic I/M program, and a program of in-use smoke opacity enforcement and random anti-tampering inspections. These scenarios are summarized in Table 4-1.

Case 1, the basic periodic I/M scenario, consists of the following elements.

- Periodic, annual inspections enforced through the registration process.
- Decentralized, garage-based inspection program, using chassis dynamometer test procedures for smoke opacity and gaseous pollutant concentration in specific operating modes.
- Visual or functional check of emission control such as EGR valves, trap bypass valves, timing advance units, etc.
- Anti-tampering inspection of trap-oxidizer, catalytic converter, fuel injection system seals, etc.

TABLE 4-1. I/M SCENARIOS CONSIDERED

Case	Inspection	Frequency	Cost Limit	Gaseous Emissions ?
1	Decentralized	Annual	\$1,000	Yes
1a	Centralized	Annual	1,000	Yes
1b	Decentralized	Annual	500	Yes
1c	Decentralized	Annual	None	Yes
1d	Decentralized	Annual	1,000	No
1e	Decentralized	Biennial	1,000	Yes
1f	Decentralized	Biennial	100	Yes
2	In-use	Variable	1,000	No
2a	In-use	Variable	None	No

- Regulations requiring fuel injection system adjustments to be sealed by an authorized shop, and making breaking the seal prima facie evidence of tampering.
- \$1,000 cost limit for repairs, no cost limit for correcting tampering. Cost waivers require approval by a referee station.
- Overall program administrative and enforcement structure similar to the existing Smog Check, but with aggressive undercover enforcement and expanded mechanic training.

Cases 1a through 1f consist of variations on this basic scenario. In Case 1a, inspection is performed in central, state-operated inspection stations, rather than in truck garages. In Case 1b, the repair cost limit is reduced to \$500. In Case 1c, the repair cost limit is eliminated--i.e. "fix it or park it". In Case 1d, the gaseous pollutant concentration measurements are eliminated, reducing the cost of the program, but also reducing its effectiveness for NO<sub>x</sub> and HC control. Case 1e is a biennial inspection program. Case 1f, the final variation, reflects the legal constraints of the current Smog Check legislation. These include: biennial inspection, \$100 cost limit, and a limit on the charge for a Smog Certificate of \$6.00.

Case 2 describes a very different I/M program based on in-use smoke opacity enforcement and anti-tampering inspections. Key features of this program are the following.

- ARB Smoke Inspectors stationed at CHP truck scales and inspection stations, maintaining continuous visual screening for excessive smoke, and with the authority to pull a truck over for a smoke test and/or anti-tampering inspection.
- Trucks cited for excessive smoke must be repaired and test below the standards within two weeks, or receive a cost waiver.

The cost limit for repairs is \$1,000. Smoke tests after repairs may be performed by BAR-authorized garages.

- Trucks cited for excessive smoke more than once in 6 months are subject to a \$250 fine (except where the first citation resulted in a waiver).
- Tampering with emission controls, or knowingly operating a truck with tampered controls, is subject to a \$1,000 fine for the first offense, and \$2,500 fine for each subsequent occurrence. Tampering must be corrected immediately, with no cost limit.
- ARB Inspectors accompanying CHP depot truck inspection teams to conduct anti-tampering inspections at the same time the CHP conducts safety inspections.
- Regulations requiring fuel injection system adjustments to be sealed by an authorized shop. Breaking the seal is prima facie evidence of tampering.
- \$1,000 cost limit for repairs, no cost limit for correcting tampering. Cost waivers require approval by a referee station.
- Tightening the existing truck smoke law, training State and local police in smoke enforcement, and issuing traffic police with opacimeters.
- Dedicated roving smoke patrol officers in critical air pollution areas such as the South Coast.

A variant, Case 2a, consists of the same program with no repair cost limit.

## 4.2 Results and Conclusions

### 4.2.1 Pollutant Emissions and Offensive Smoke

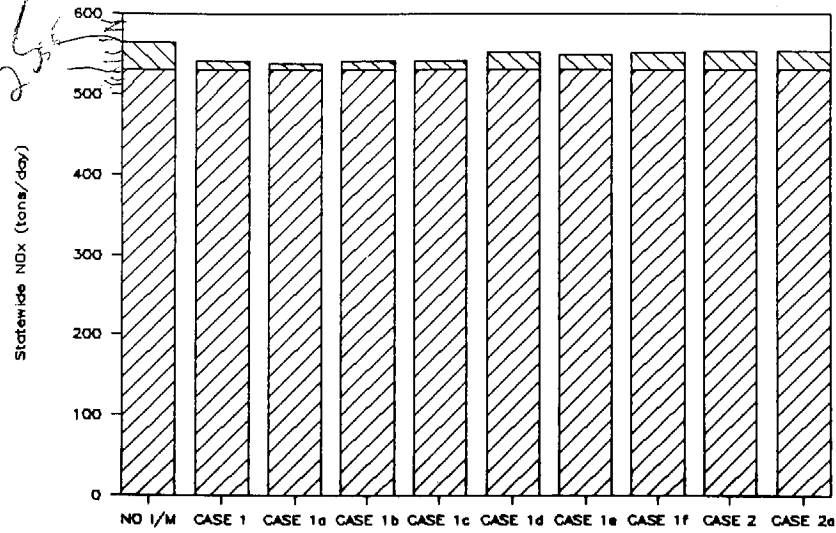
Pollutant emissions--Figures 4-1 through 4-3 show the total emission projected under each I/M scenario for the years 1990, 1995, and 2000. Figures 4-4 and 4-5 provide more detail on the reductions in excess emissions under each scenario. Figure 4-4 shows the emissions reduction for each pollutant (in tons/day, statewide) in 1990, 1995, and 2000, while Figure 4-5 shows the percentage reduction in excess emissions of each pollutant for the same years.

Several features of the data presented in these figures are worthy of note. First, excess  $\text{NO}_x$  emissions (while large in absolute terms) are only a small fraction of the total diesel  $\text{NO}_x$ . Thus, although some programs can reduce excess  $\text{NO}_x$  significantly, this effect is small relative to total  $\text{NO}_x$  emissions. This is not the case with HC or PM emissions. Since excess emissions of these pollutants account for a large fraction of the total, an I/M program which significantly reduces these excess emissions can have a large effect relative to the total.

As Figure 4-4 indicates, all of the annual inspection programs are reasonably effective in reducing excess  $\text{NO}_x$ , but they are less effective in reducing HC and PM emissions. The centralized program in Case 1a is marginally more effective in this regard, reflecting the greater probability of deterring or detecting tampering with the central inspection. All of these programs are hampered, however, by their relatively infrequent and predictable inspections, which limit the deterrence of "reversible" tampering, and which do relatively little to reduce the overall incidence of non-tampered high-emitting vehicles. The in-use inspection programs, on the other hand, are highly effective in reducing particulate and HC emissions--resulting in more than a 50 percent reduction in excess PM. These programs are less effective in reducing  $\text{NO}_x$ , however, especially in the earlier years of the program.

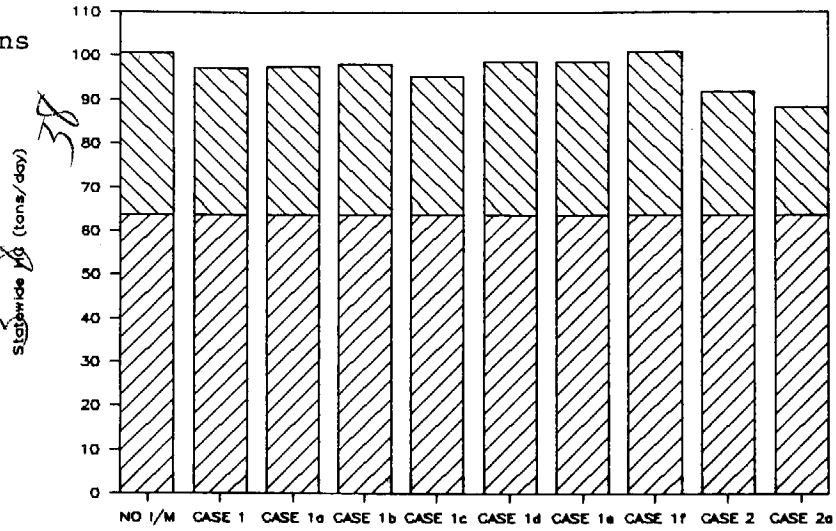
NO<sub>x</sub>

500/6  
2



Hydrocarbons

100  
60  
38



Particulate

100  
50  
67

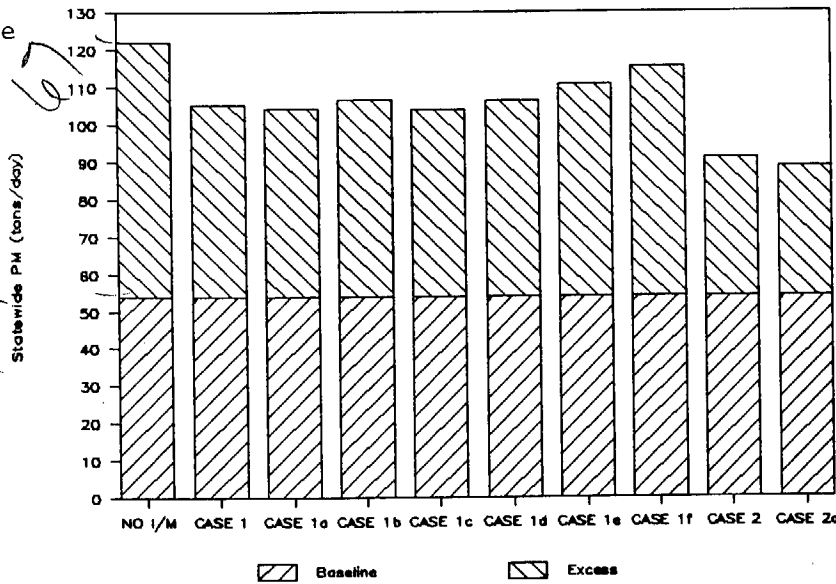
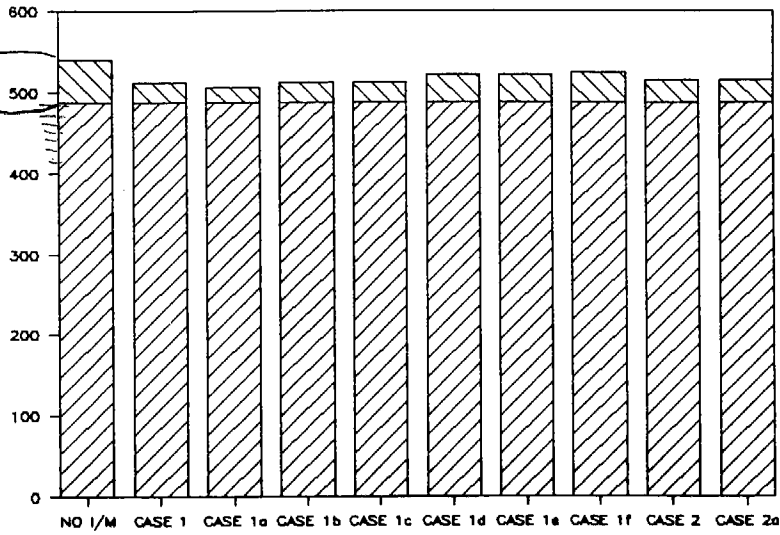


Figure 4-1. Comparison of I/M Scenarios: Total Emissions - 1990

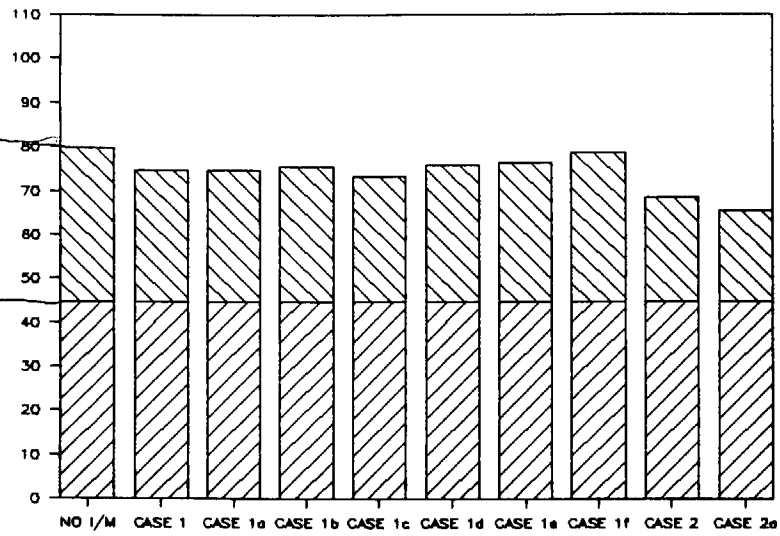
NO<sub>x</sub>

Statewide NO<sub>x</sub> (tons/day)



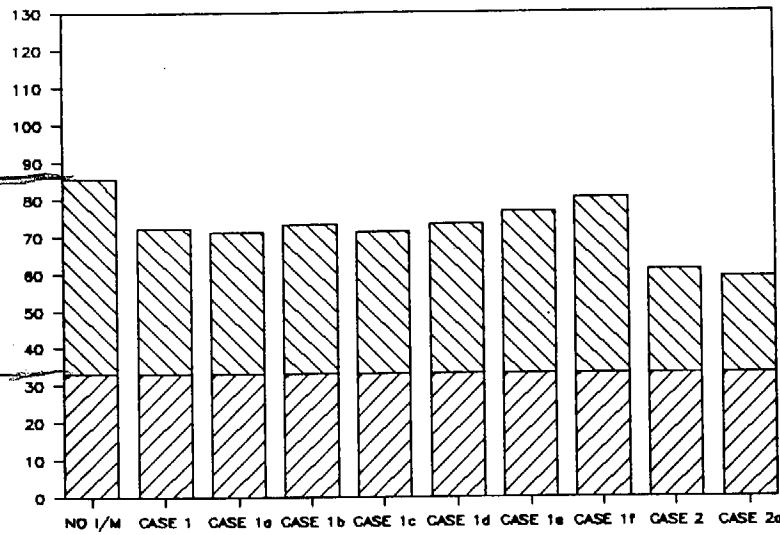
Hydrocarbons

Statewide HC (tons/day)



Particulate

Statewide PM (tons/day)



Baseline

Excess

Figure 4-2. Comparison of I/M Scenarios: Total Emissions - 1995

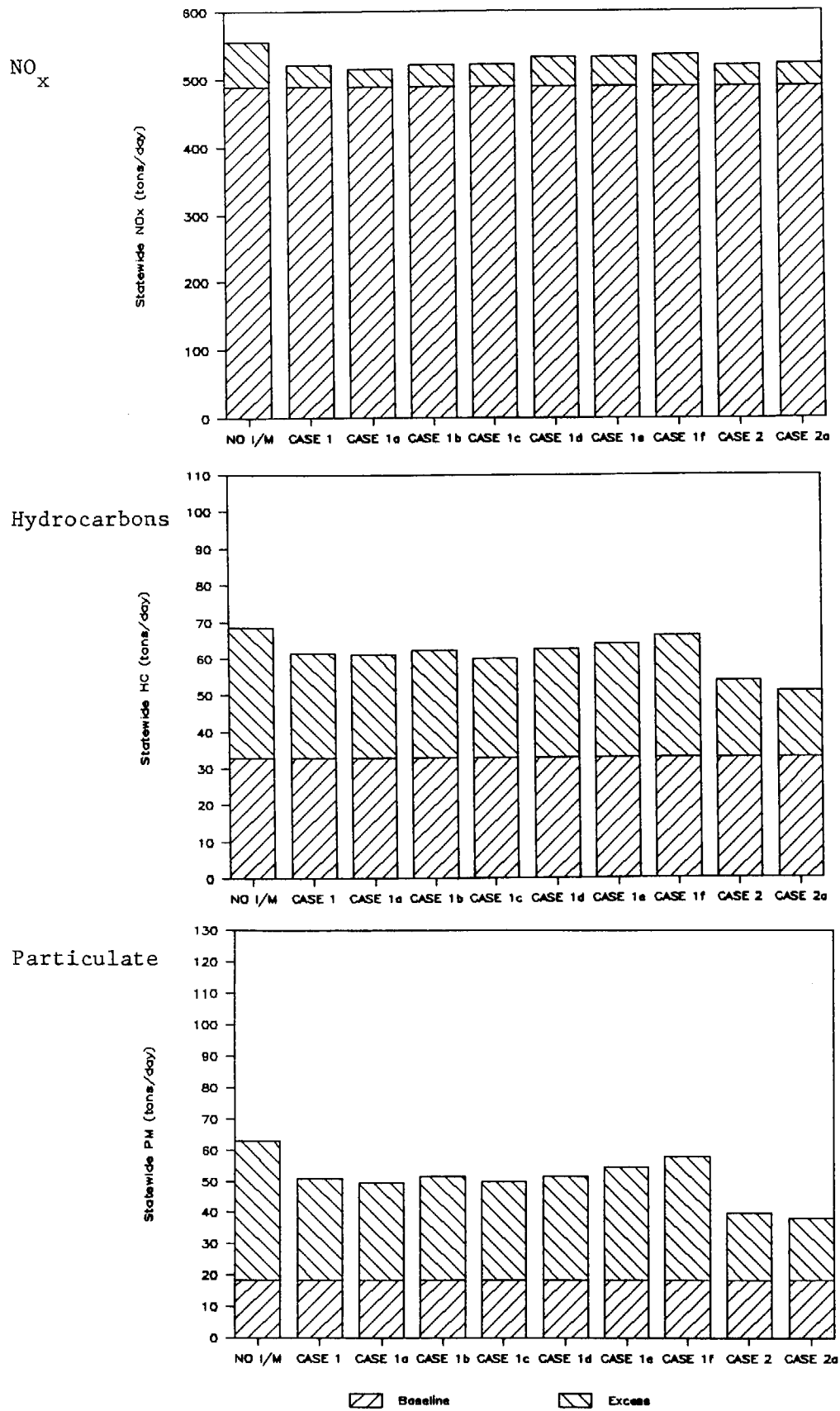
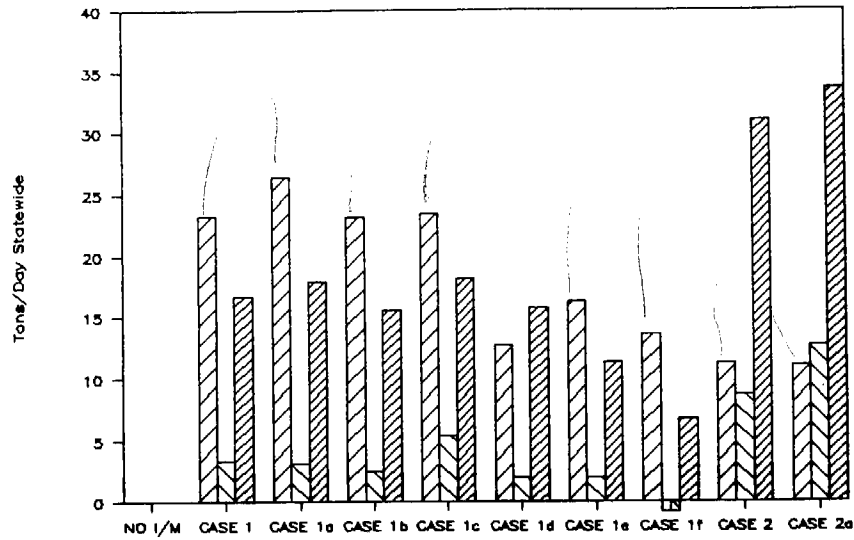
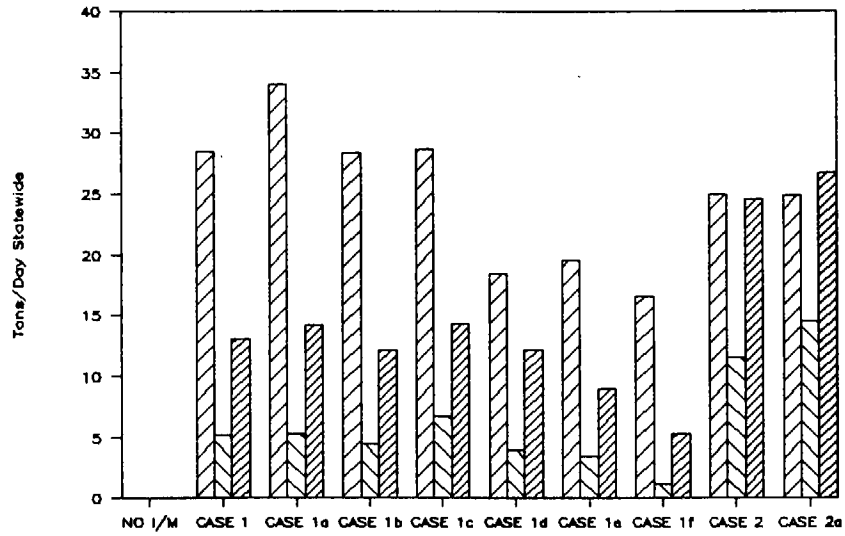


Figure 4-3. Comparison of I/M Scenarios: Total Emissions - 2000

1990



1995



2000

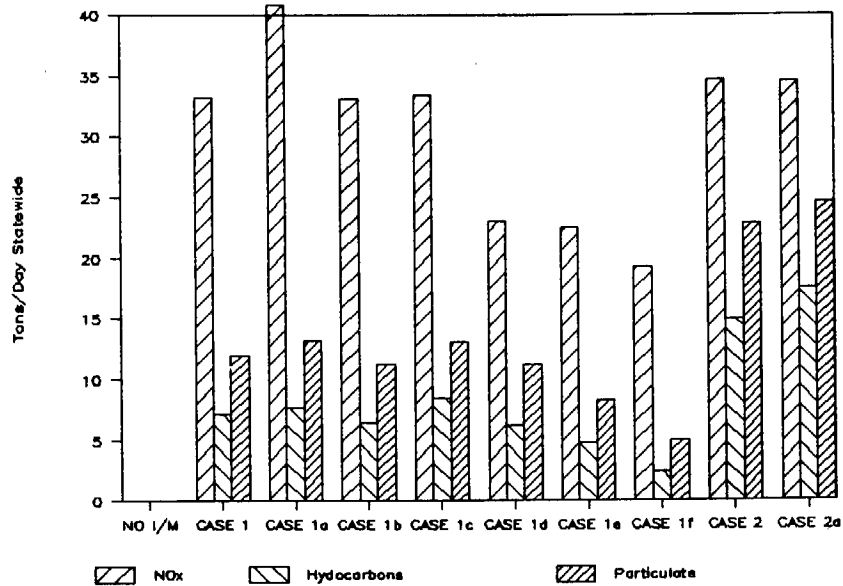
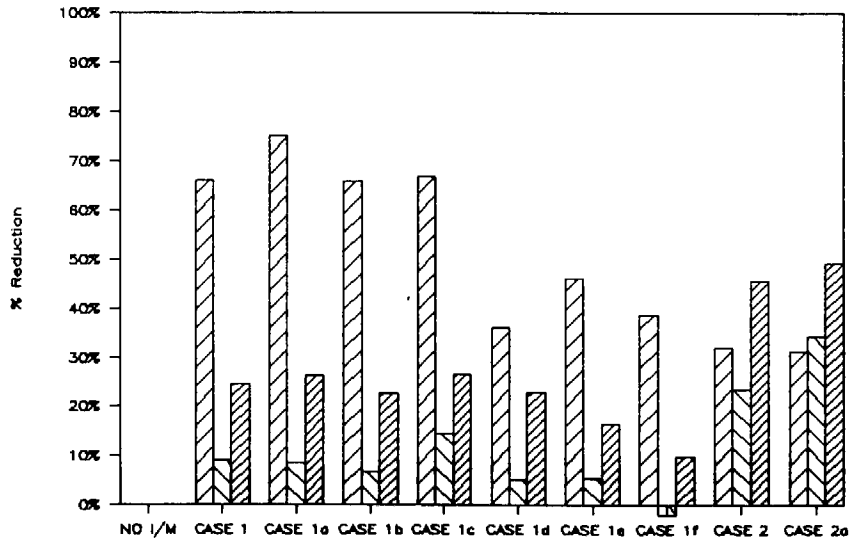
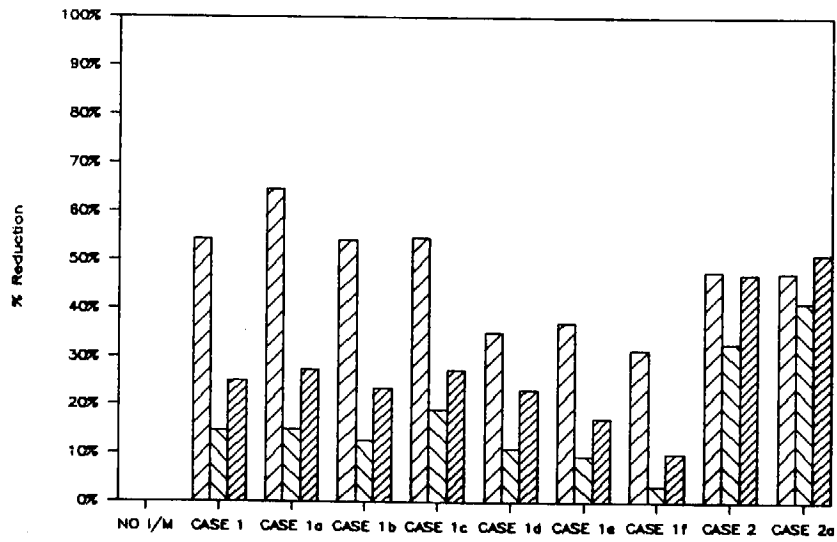


Figure 4-4. Comparison of I/M Scenarios: Reduction in Emissions Due to I/M

1990



1995



2000

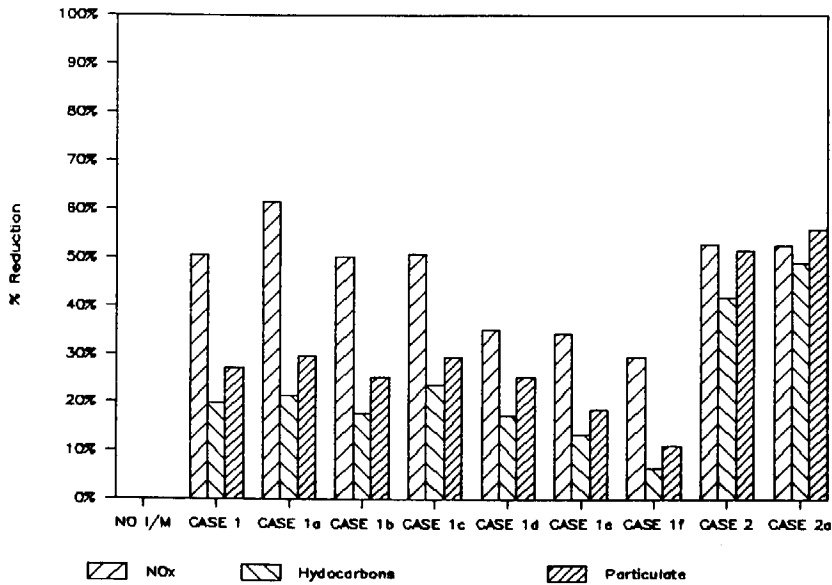


Figure 4-5. Comparison of I/M Scenarios: Percent Reduction in Excess Emissions Due to I/M

Offensive smoke--Figure 4-6 shows the offensive smoke index calculated for each of the I/M scenarios and the baseline case with no I/M. Also shown is the percentage reduction in the offensive smoke index under each I/M scenario. This index is an artificial value based on the frequency of occurrence of emissions defects which result in high smoke emissions. It is intended to represent the rough fraction of trucks on the road exhibiting offensive smoke levels in any operating mode.

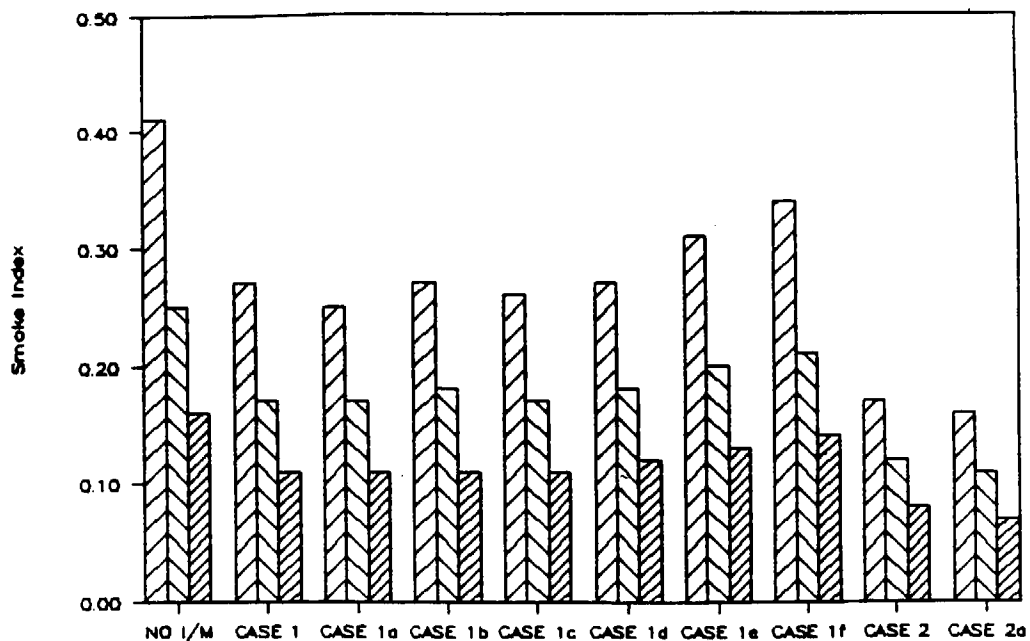
As Figure 4-6 shows, the two in-use I/M scenarios produced large reductions in the offensive smoke index, while the periodic I/M scenarios had a smaller, but still significant, effect. Regardless of the scenario, the overall incidence of offensive smoke is projected to decline markedly between 1990 and 2000, as trucks built to the 1991 and 1994 particulate standards come to dominate the fleet.

#### 4.2.2 Costs and Cost-Effectiveness

Tables 4-2 through 4-4 display the estimated costs to truck owners, the government, and society as a whole due to each I/M scenario. In each scenario except Case 1e, government revenues from Smog Certificate fees or fines for tampering were projected to approximate or exceed the government's costs--thus, the net cost to the government is small or negative. Tables 4-2 through 4-4 also show the net reduction in emissions due to each program, and the cost-effectiveness of each program for particulate emissions control. Overall cost-effectiveness estimates for each scenario are summarized in Figure 4-7.

To calculate the cost-effectiveness of an emissions control strategy--such as I/M--which affects more than one pollutant requires that some assumptions be made as to the proper allocation of costs between the different pollutants. For our calculations, we assigned each program a credit of \$4,000 per ton of NO<sub>x</sub> or HC reduced, and assigned the remaining costs of the program to particulate control. Making these assumptions, we were able to calculate

Offensive Smoke Index



% Reduction in Offensive Smoke Index

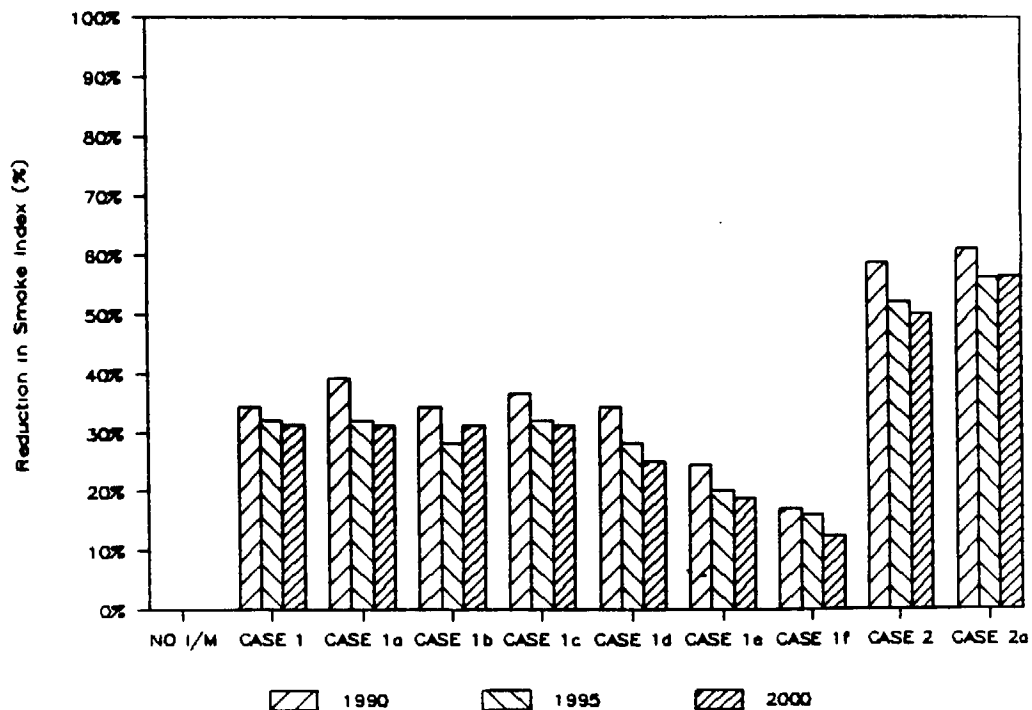


Figure 4-6. Comparison of I/M Scenarios: Reduction of Offensive Smoke Due to I/M

TABLE 4-2. COSTS AND COST EFFECTIVENESS OF ALTERNATIVE I/M PROGRAM DESIGNS: 1990

	Case 1	Case 1a	Case 1b	Case 1c	Case 1d	Case 1e	Case 1f	Case 2	Case 2a
<u>Program Cost (millions of dollars)</u>									
<u>Costs to Truck Owners</u>									
Smog Certificates	4.44	26.09	4.44	4.44	4.44	4.44	0.78	0.00	0.00
Private Inspections	23.76	0.00	23.31	24.32	19.42	11.88	11.19	4.06	4.52
Non-Tampering Repairs	15.89	16.29	12.13	49.22	11.26	7.94	0.88	23.88	77.65
Tampering Repairs	8.98	8.08	8.90	8.98	8.79	4.49	5.68	5.73	5.73
Lost Time	29.81	38.63	28.99	30.81	28.06	14.90	13.70	21.71	23.19
Fines	0.00	0.00	0.00	0.00	0.00	0.00	0.00	13.34	13.34
Fuel Consumption	-8.2	-8.8	-7.6	-8.9	-8.8	-5.2	-2.4	-16.2	-17.2
<b>Total Cost to Owners</b>	<b>74.7</b>	<b>80.3</b>	<b>70.2</b>	<b>108.9</b>	<b>83.1</b>	<b>38.4</b>	<b>29.6</b>	<b>52.5</b>	<b>107.2</b>
<u>Costs to Government</u>									
Program Costs	4.4	26.7	4.4	4.4	4.4	4.4	4.4	6.8	6.8
Fees and Fines	-4.4	-26.1	-4.4	-4.4	-4.4	-4.4	-0.8	-13.3	-13.3
<b>Total Cost to Government</b>	<b>0.0</b>	<b>0.6</b>	<b>0.0</b>	<b>0.0</b>	<b>0.0</b>	<b>0.0</b>	<b>3.7</b>	<b>-6.5</b>	<b>-6.5</b>
<b>Total Social Cost</b>	<b>74.7</b>	<b>80.9</b>	<b>70.2</b>	<b>108.9</b>	<b>83.1</b>	<b>38.4</b>	<b>33.3</b>	<b>46.0</b>	<b>100.6</b>
<u>Emission Reductions (tons/day)</u>									
Oxides of Nitrogen	23.3	26.4	23.1	23.5	12.7	16.3	13.6	11.3	11.0
Unburned Hydrocarbons	3.3	3.2	2.5	5.4	1.9	2.0	-0.3	8.7	12.6
Particulate Matter	16.7	17.9	15.5	18.1	15.7	11.4	6.7	31.1	33.6
<u>Cost-Effectiveness (\$/Ton)</u>									
NOx	\$4,000	\$4,000	\$4,000	\$4,000	\$4,000	\$4,000	\$4,000	\$4,000	\$4,000
HC	\$4,000	\$4,000	\$4,000	\$4,000	\$4,000	\$4,000	\$4,000	\$4,000	\$4,000
PM	\$5,869	\$5,784	\$5,779	\$10,087	\$7,273	\$2,836	\$5,661	\$1,489	\$5,388
<b>Cost-Effectiveness (\$/ton PM)*</b>	<b>\$2,330</b>	<b>\$1,210</b>	<b>\$2,000</b>	<b>\$6,770</b>	<b>\$3,930</b>	<b>\$502</b>	<b>\$1,066</b>	<b>(Neg)**</b>	<b>\$3,816</b>
<u>W/O Indirect costs and savings</u>									

\* Indirect costs are lost time and fuel consumption.

 \*\* Negative cost after taking NO<sub>x</sub> and HC credits.

TABLE 4-3. COSTS AND COST EFFECTIVENESS OF ALTERNATIVE I/M PROGRAM DESIGNS: 1995

	Case 1	Case 1a	Case 1b	Case 1c	Case 1d	Case 1e	Case 1f	Case 2	Case 2a
<u>Program Cost (millions of dollars)</u>									
<u>Costs to Truck Owners</u>									
Smog Certificates	5.88	34.60	5.88	5.88	5.88	5.88	1.04	0.00	0.00
Private Inspections	30.04	0.00	29.44	30.80	24.45	14.41	14.25	4.78	5.40
Non-Tampering Repairs	20.08	20.69	14.84	64.84	14.50	8.16	0.71	29.04	99.95
Tampering Repairs	11.43	10.14	11.32	11.43	10.60	4.42	7.65	8.31	8.31
Lost Time	37.33	47.54	36.24	38.73	35.05	17.57	17.29	25.35	27.29
Fines	0.00	0.00	0.00	0.00	0.00	0.00	0.00	15.95	15.95
Fuel Consumption	-1.1	-0.4	-0.8	-1.5	-1.9	-0.5	1.2	-4.3	-5.1
<b>Total Cost to Owners</b>	<b>103.7</b>	<b>112.5</b>	<b>97.1</b>	<b>150.1</b>	<b>88.6</b>	<b>50.0</b>	<b>42.1</b>	<b>79.1</b>	<b>151.8</b>
<u>Costs to Government</u>									
Program Costs	5.9	34.6	5.9	5.9	5.9	5.9	5.9	9.0	9.0
Fees and Fines	-5.9	-34.6	-5.9	-5.9	-5.8	-5.9	-1.0	-16.0	-16.0
<b>Total Cost to Government</b>	<b>0.0</b>	<b>0.0</b>	<b>0.0</b>	<b>0.0</b>	<b>0.0</b>	<b>0.0</b>	<b>4.8</b>	<b>-7.0</b>	<b>-7.0</b>
<b>Total Social Cost</b>	<b>103.7</b>	<b>112.5</b>	<b>97.1</b>	<b>150.1</b>	<b>88.6</b>	<b>50.0</b>	<b>47.0</b>	<b>72.1</b>	<b>144.8</b>
<u>Emission Reductions (tons/day)</u>									
Oxides of Nitrogen	28.5	34.0	28.4	28.7	18.5	19.5	16.6	25.0	24.9
Unburned Hydrocarbons	5.1	5.3	4.4	6.7	4.0	3.4	1.2	11.5	14.5
Particulate Matter	13.1	14.2	12.2	14.3	12.2	9.0	5.3	24.6	26.7
<u>Cost-Effectiveness (\$/ton)</u>									
NOx	\$4,000	\$4,000	\$4,000	\$4,000	\$4,000	\$4,000	\$4,000	\$4,000	\$4,000
HC	\$4,000	\$4,000	\$4,000	\$4,000	\$4,000	\$4,000	\$4,000	\$4,000	\$4,000
PM	\$11,396	\$10,826	\$11,042	\$18,855	\$12,568	\$5,038	\$10,868	\$2,101	\$8,959
<b>Cost-Effectiveness (\$/ton PM)*</b>	<b>\$3,825</b>	<b>\$1,546</b>	<b>\$3,049</b>	<b>\$11,731</b>	<b>\$5,102</b>	<b>**(Neg)</b>	<b>\$1,342</b>	<b>**(Neg)</b>	<b>\$5,046</b>
<u>W/O Indirect costs and savings</u>									

\* Indirect costs are lost time and fuel consumption.

 \*\* Negative cost after taking NO<sub>x</sub> and HC credits.

TABLE 4-4. COSTS AND COST EFFECTIVENESS OF ALTERNATIVE I/M PROGRAM DESIGNS: 2000

	Case 1	Case 1a	Case 1b	Case 1c	Case 1d	Case 1e	Case 1f	Case 2	Case 2a
<u>Program Cost (millions of dollars)</u>									
<u>Costs to Truck Owners</u>									
Smog Certificates	7.02	41.31	7.02	7.02	7.02	7.02	1.24	0.00	0.00
Private Inspections	35.16	0.00	34.43	36.11	28.62	18.90	16.75	5.47	6.24
Non-Tampering Repairs	24.34	25.23	17.68	78.16	18.22	10.10	0.72	34.45	119.12
Tampering Repairs	14.33	12.81	14.23	14.33	13.17	5.40	9.99	11.66	11.66
Lost Time	43.54	55.06	42.20	45.28	40.94	20.53	20.25	28.81	31.18
Fines	0.00	0.00	0.00	0.00	0.00	0.00	0.00	19.31	19.31
Fuel Consumption	4.8	6.5	5.1	4.5	4.0	3.5	4.2	5.8	5.2
<b>Total Cost to Owners</b>	<b>129.2</b>	<b>140.9</b>	<b>120.7</b>	<b>185.4</b>	<b>111.9</b>	<b>63.4</b>	<b>53.1</b>	<b>105.5</b>	<b>192.8</b>
<u>Costs to Government</u>									
Program Costs	7.0	41.3	7.0	7.0	7.0	7.0	7.0	10.7	10.7
Fees and Fines	-7.0	-41.3	-7.0	-7.0	-7.0	-7.0	-1.2	-19.3	-19.3
<b>Total Cost to Government</b>	<b>0.0</b>	<b>0.0</b>	<b>0.0</b>	<b>0.0</b>	<b>0.0</b>	<b>0.0</b>	<b>5.8</b>	<b>-8.6</b>	<b>-8.6</b>
<b>Total Social Cost</b>	<b>129.2</b>	<b>140.9</b>	<b>120.7</b>	<b>185.4</b>	<b>111.9</b>	<b>63.4</b>	<b>58.9</b>	<b>96.9</b>	<b>184.2</b>
<u>Emission Reductions (tons/day)</u>									
Oxides of Nitrogen	39.2	40.4	38.1	38.4	28.0	22.6	19.3	34.6	34.6
Unburned Hydrocarbons	7.1	7.6	6.4	8.5	6.2	4.8	2.4	14.9	17.5
Particulate Matter	12.0	19.1	11.2	13.0	11.2	8.2	5.0	22.8	24.6
<u>Cost-Effectiveness (\$/ton)</u>									
NOx	\$4,000	\$4,000	\$4,000	\$4,000	\$4,000	\$4,000	\$4,000	\$4,000	\$4,000
HC	\$4,000	\$4,000	\$4,000	\$4,000	\$4,000	\$4,000	\$4,000	\$4,000	\$4,000
PM	\$16,102	\$14,734	\$15,408	\$26,145	\$16,983	\$7,805	\$15,087	\$2,942	\$12,023
<b>Cost-Effectiveness (\$/ton PM)*</b>	<b>\$5,033</b>	<b>\$1,908</b>	<b>\$3,836</b>	<b>\$15,666</b>	<b>\$5,983</b>	<b>** [Neg]</b>	<b>\$1,606</b>	<b>** [Neg]</b>	<b>\$5,823</b>
<u>W/O Indirect costs and savings</u>									

\* Indirect costs are lost time and fuel consumption.

 \*\* Negative cost after taking NO<sub>x</sub> and HC credits.

the cost-effectiveness of each program as a particulate control measure, treating the HC and NO<sub>x</sub> reduction benefits as side-effects. The value of \$4,000 per ton of HC and NO<sub>x</sub> eliminated is fairly typical of other ongoing emission control initiatives in California, although many approaches with higher and lower cost-effectiveness values have also been recommended.

As Figure 4-7 shows, the most cost-effective I/M program scenario by our calculations is Case 2. Case 2 also results in the second largest reduction in emissions (after Case 2a), and thus appears clearly preferable overall. Case 2 is followed in cost-effectiveness by the other cost-limited periodic inspection programs. These are grouped fairly closely in cost-effectiveness and overall results, although Case 1a (centralized inspection) has somewhat of an advantage. This shows that centralized inspection is superior to even an effectively administered and enforced decentralized program. The advantage of centralized inspection over a less vigorously enforced decentralized program would be much greater.

Some of the highest costs-per-ton of emissions control are calculated for the two scenarios with no repair cost limits, due to the very high costs of engine overhaul included in these cases. These calculations overestimate the actual economic costs somewhat, since overhauling an engine increases its value and useful life. Nonetheless, it appears that some reasonable limit on repair costs is needed in a heavy-duty diesel I/M program in order to keep overall program costs and cost-effectiveness reasonable.

The cost-effectiveness calculations shown in the tables include an explicit accounting for "indirect" costs and benefits to the truck owners, such as lost driver and truck time, and fuel consumption effects. These are a large fraction of the total costs of the program. For compatibility, with some other cost-effectiveness estimates for I/M programs, we also calculated the cost-effectiveness omitting these cost elements. Omitting these elements reduces the calculated cost of the program considerably--to the point that this cost is less than the credit for HC and NO<sub>x</sub> reductions, in some cases.

Cost-Effectiveness for Particulate Control

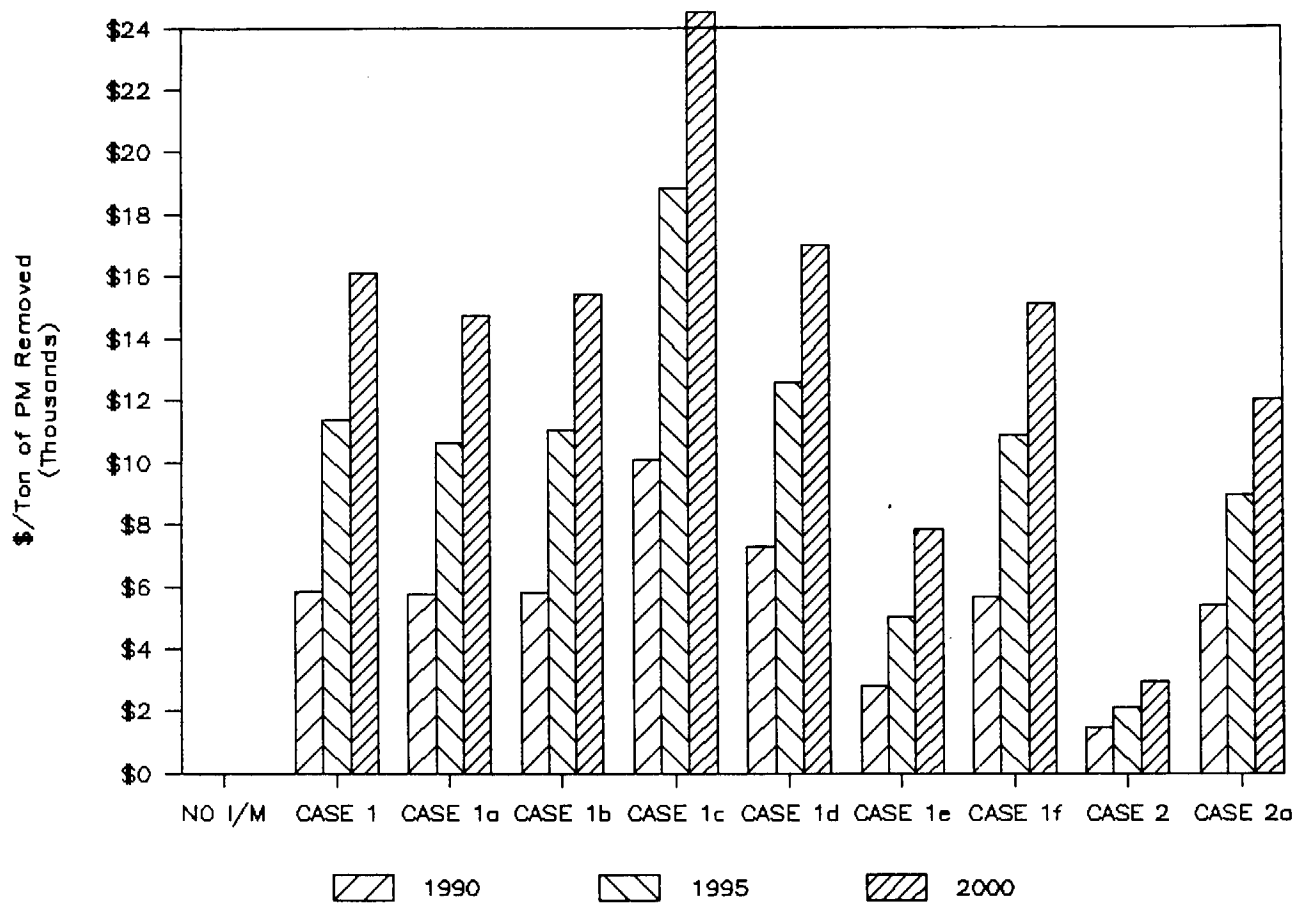


Figure 4-7. Comparison of I/M Scenarios: Cost Effectiveness